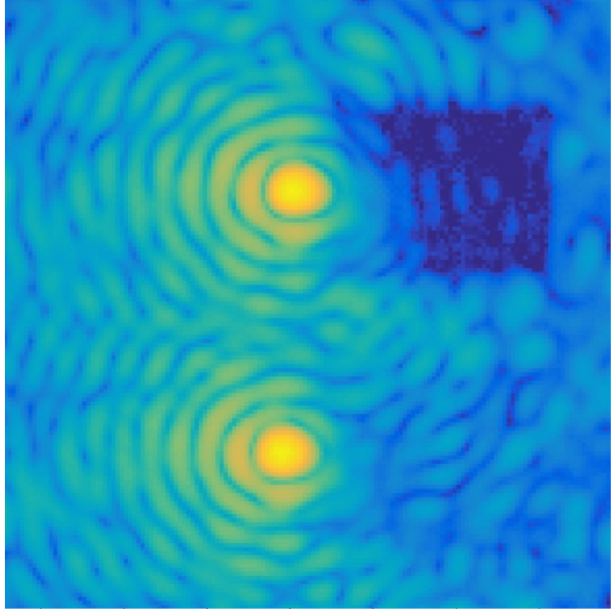
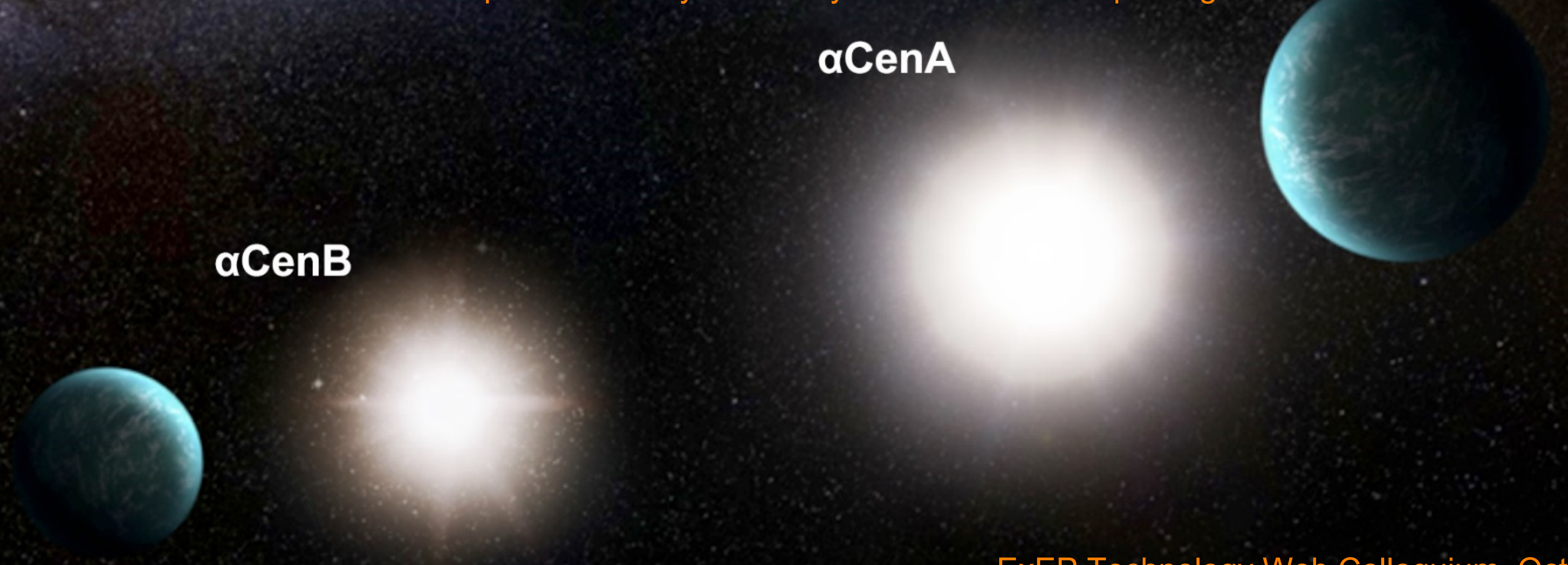
Multi-Star Wavefront Control: A Method for Exoplanet Imaging in Multi-Star Systems



Ruslan Belikov, Eduardo Bendek, Dan Sirbu, Eugene Pluzhnik, Elias Holte
(NASA Ames Research Center)
Sandrine Thomas (LSST)
Olivier Guyon (University of Arizona)

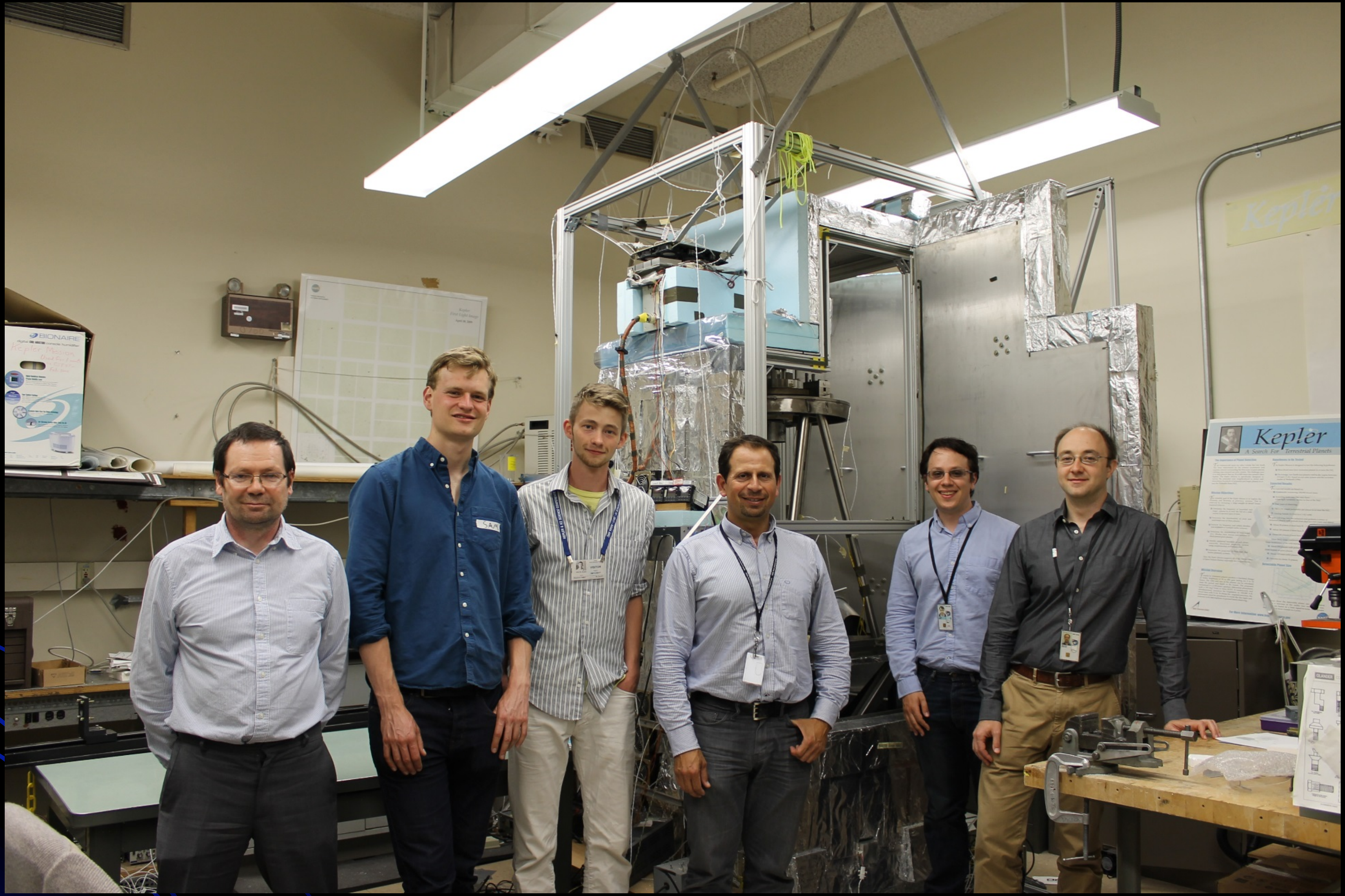
NASA Ames
Exoplanet Technologies Group

Supported by NASA SMD's APRA program and ARC CIF+IRAD (4/2015 – 3/2017, work successfully completed)
Continued development recently funded by HQ directed work package based on SAT / TDEM proposal



ExEP Technology Web Colloquium, October 24, 2017

Exoplanets Technologies group at NASA ARC



Eugene Pluzhnik
Sam Harrison
Elias Holte
Eduardo Bendek
Dan Sirbu
Rus Belikov

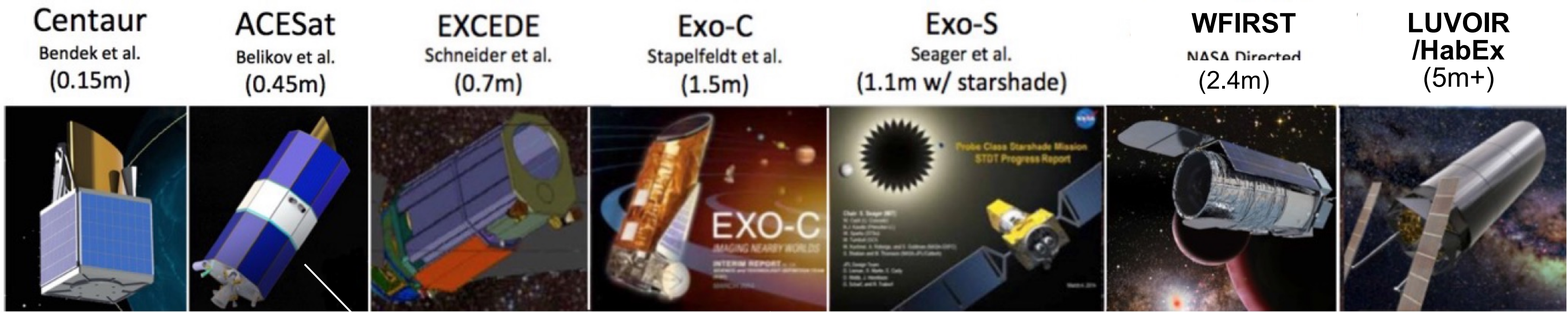
Part-time members (not pictured): Pete Zell, Fred Witteborn, Jack Lissauer, Steve Bryson, Chris Henze

Importance of Multi-Star Systems

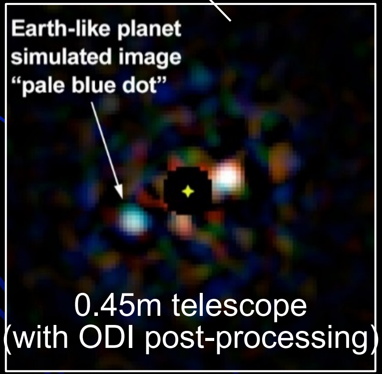
- Most non-Mdwarf stars are in multi-star systems. For example, within 4pc:
  - 5 Multiples: aCen, Sirius, Procyon, 61 Cyg, e Ind
  - 2 Single: e Eri, t Cet

- Alpha Centauri is an unusually favorable outlier

Missions that can benefit from multi-star suppression

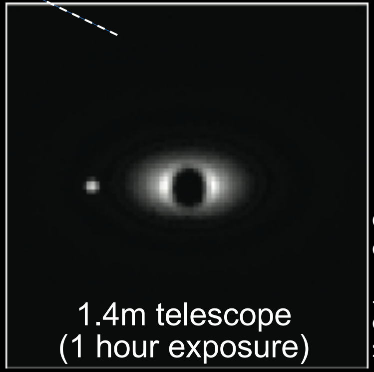


Belikov et al. 2015
Bendek et al. 2015



0.45m telescope
(with ODI post-processing)

J. Males, R. Belikov

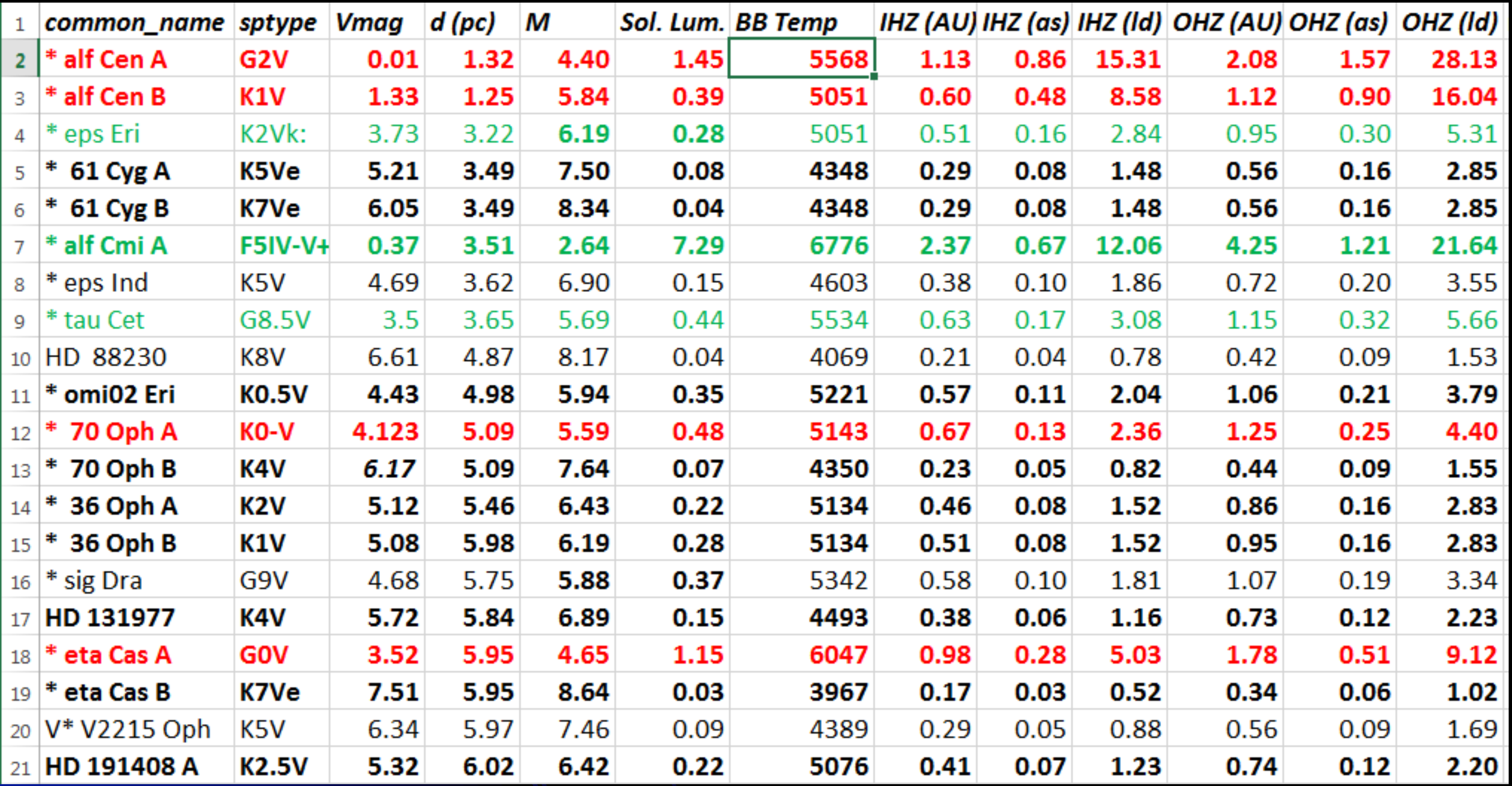


1.4m telescope
(1 hour exposure)

K. Cahoy, O. Guyon

Simulations of exo-Earth detections around Alpha Centauri A
(if the other star could be suppressed)

Nearby FGK Targets for WFIRST



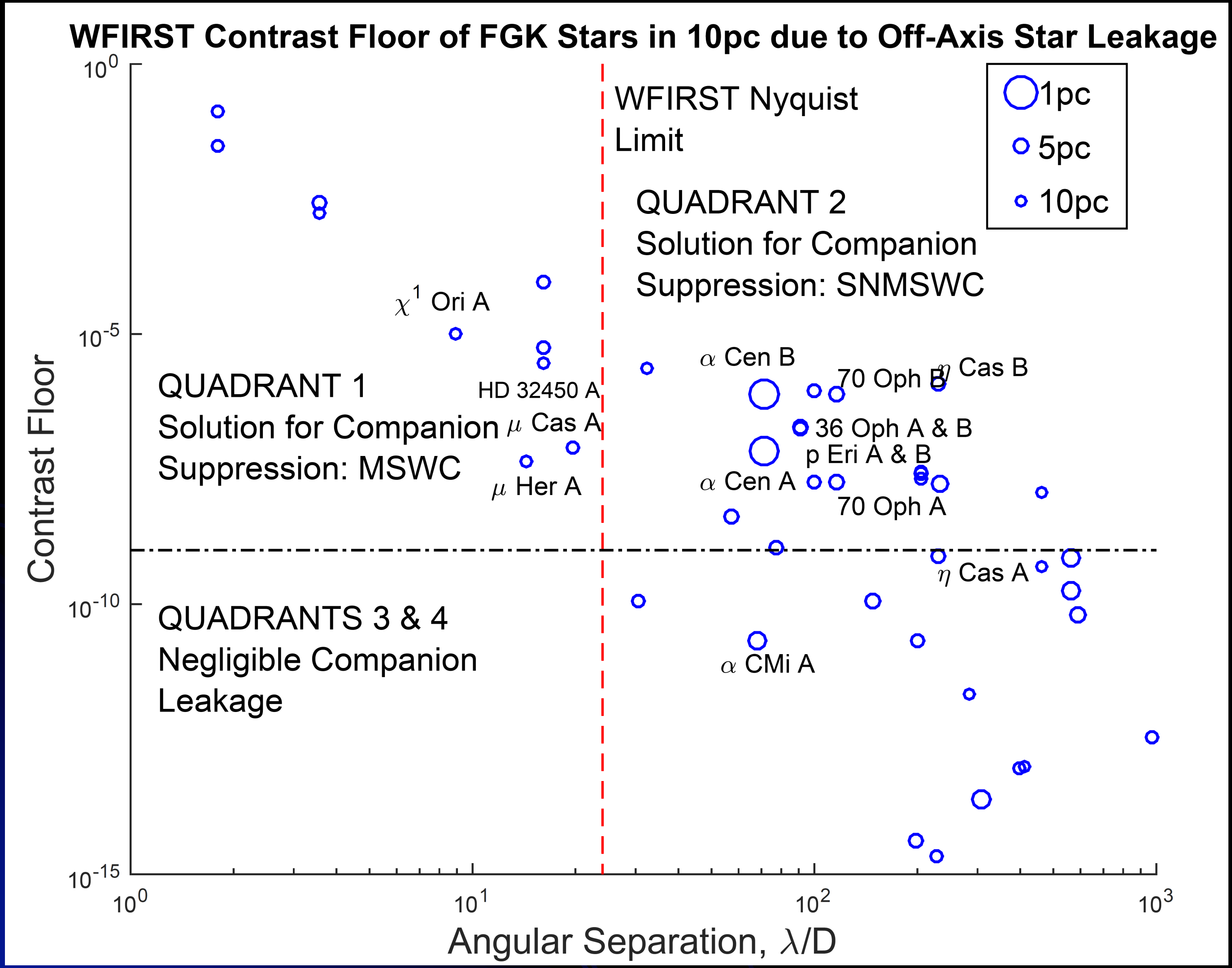
1	common_name	sptype	Vmag	d (pc)	M	Sol. Lum.	BB Temp	IHZ (AU)	IHZ (as)	IHZ (ld)	OHZ (AU)	OHZ (as)	OHZ (ld)
2	*** alf Cen A**	**G2V**	**0.01**	**1.32**	**4.40**	**1.45**	**5568**	**1.13**	**0.86**	**15.31**	**2.08**	**1.57**	**28.13**
3	*** alf Cen B**	**K1V**	**1.33**	**1.25**	**5.84**	**0.39**	**5051**	**0.60**	**0.48**	**8.58**	**1.12**	**0.90**	**16.04**
4	* eps Eri	K2Vk:	3.73	3.22	**6.19**	**0.28**	5051	0.51	0.16	2.84	0.95	0.30	5.31
5	*** 61 Cyg A**	**K5Ve**	**5.21**	**3.49**	**7.50**	**0.08**	**4348**	**0.29**	**0.08**	**1.48**	**0.56**	**0.16**	**2.85**
6	*** 61 Cyg B**	**K7Ve**	**6.05**	**3.49**	**8.34**	**0.04**	**4348**	**0.29**	**0.08**	**1.48**	**0.56**	**0.16**	**2.85**
7	*** alf Cmi A**	**F5IV-V+**	**0.37**	**3.51**	**2.64**	**7.29**	**6776**	**2.37**	**0.67**	**12.06**	**4.25**	**1.21**	**21.64**
8	* eps Ind	K5V	4.69	3.62	6.90	0.15	4603	0.38	0.10	1.86	0.72	0.20	3.55
9	* tau Cet	G8.5V	3.5	3.65	5.69	0.44	5534	0.63	0.17	3.08	1.15	0.32	5.66
10	HD 88230	K8V	6.61	4.87	8.17	0.04	4069	0.21	0.04	0.78	0.42	0.09	1.53
11	*** omi02 Eri**	**K0.5V**	**4.43**	**4.98**	**5.94**	**0.35**	**5221**	**0.57**	**0.11**	**2.04**	**1.06**	**0.21**	**3.79**
12	*** 70 Oph A**	**K0-V**	**4.123**	**5.09**	**5.59**	**0.48**	**5143**	**0.67**	**0.13**	**2.36**	**1.25**	**0.25**	**4.40**
13	*** 70 Oph B**	**K4V**	*6.17*	**5.09**	**7.64**	**0.07**	**4350**	**0.23**	**0.05**	**0.82**	**0.44**	**0.09**	**1.55**
14	*** 36 Oph A**	**K2V**	**5.12**	**5.46**	**6.43**	**0.22**	**5134**	**0.46**	**0.08**	**1.52**	**0.86**	**0.16**	**2.83**
15	*** 36 Oph B**	**K1V**	**5.08**	**5.98**	**6.19**	**0.28**	**5134**	**0.51**	**0.08**	**1.52**	**0.95**	**0.16**	**2.83**
16	* sig Dra	G9V	4.68	5.75	**5.88**	**0.37**	5342	0.58	0.10	1.81	1.07	0.19	3.34
17	**HD 131977**	**K4V**	**5.72**	**5.84**	**6.89**	**0.15**	**4493**	**0.38**	**0.06**	**1.16**	**0.73**	**0.12**	**2.23**
18	*** eta Cas A**	**G0V**	**3.52**	**5.95**	**4.65**	**1.15**	**6047**	**0.98**	**0.28**	**5.03**	**1.78**	**0.51**	**9.12**
19	*** eta Cas B**	**K7Ve**	**7.51**	**5.95**	**8.64**	**0.03**	**3967**	**0.17**	**0.03**	**0.52**	**0.34**	**0.06**	**1.02**
20	V* V2215 Oph	K5V	6.34	5.97	7.46	0.09	4389	0.29	0.05	0.88	0.56	0.09	1.69
21	**HD 191408 A**	**K2.5V**	**5.32**	**6.02**	**6.42**	**0.22**	**5076**	**0.41**	**0.07**	**1.23**	**0.74**	**0.12**	**2.20**

Nearest 20 Stars:
13 Multi-Stars
4/7 Multi-Star Hab.
Zones w/in WFIRST
FOV

Legend:
BOLD – Binaries
Color – Hab.Zone
w/in WFIRST FOV
Green – Single-Star
WFC Solution
Red – Multi-Star
WFC Solution

Dan Sirbu

Multi-Star Direct Imaging Science with WFIRST



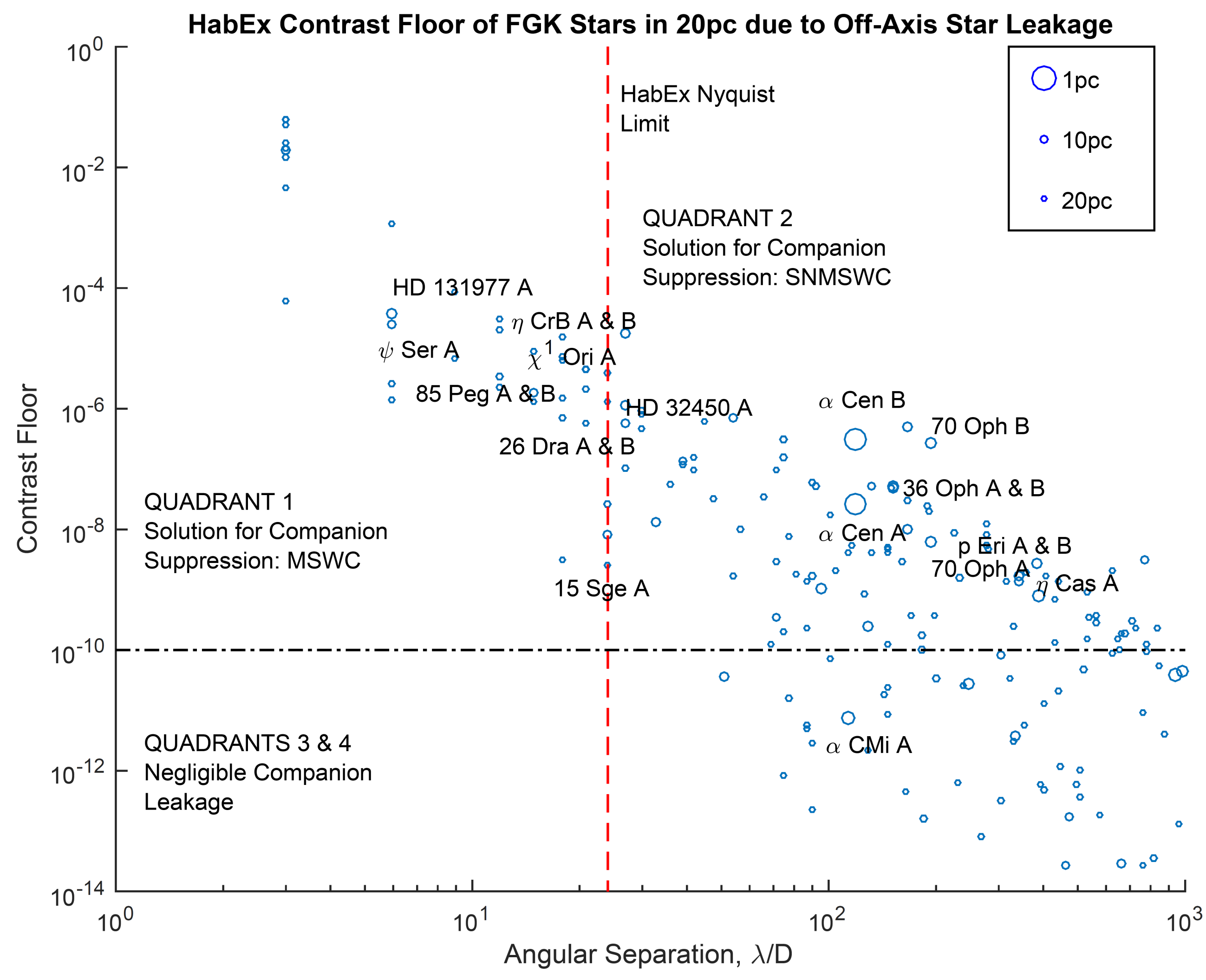
Sirbu et al. 2017, accepted by ApJ

Multi-Star Science Statistics:
- 70 FGK stars within 10pc
- 43 multi-stars (dynamical)
- 28 stars limited at > 1e-9
    - 8 stars with sep. < N/2 λ/D

WFIRST assumptions:
- D = 2.4m
- λ = 650nm
- λ/20 RMS with f^{-3} power spectrum
- 48x48 DM

Note: Contrast floor for an on-axis coronagraph/starshade due to unsuppressed off-axis companion star

Multi-Star Targets with HabEx



Multi-Star Science Statistics:

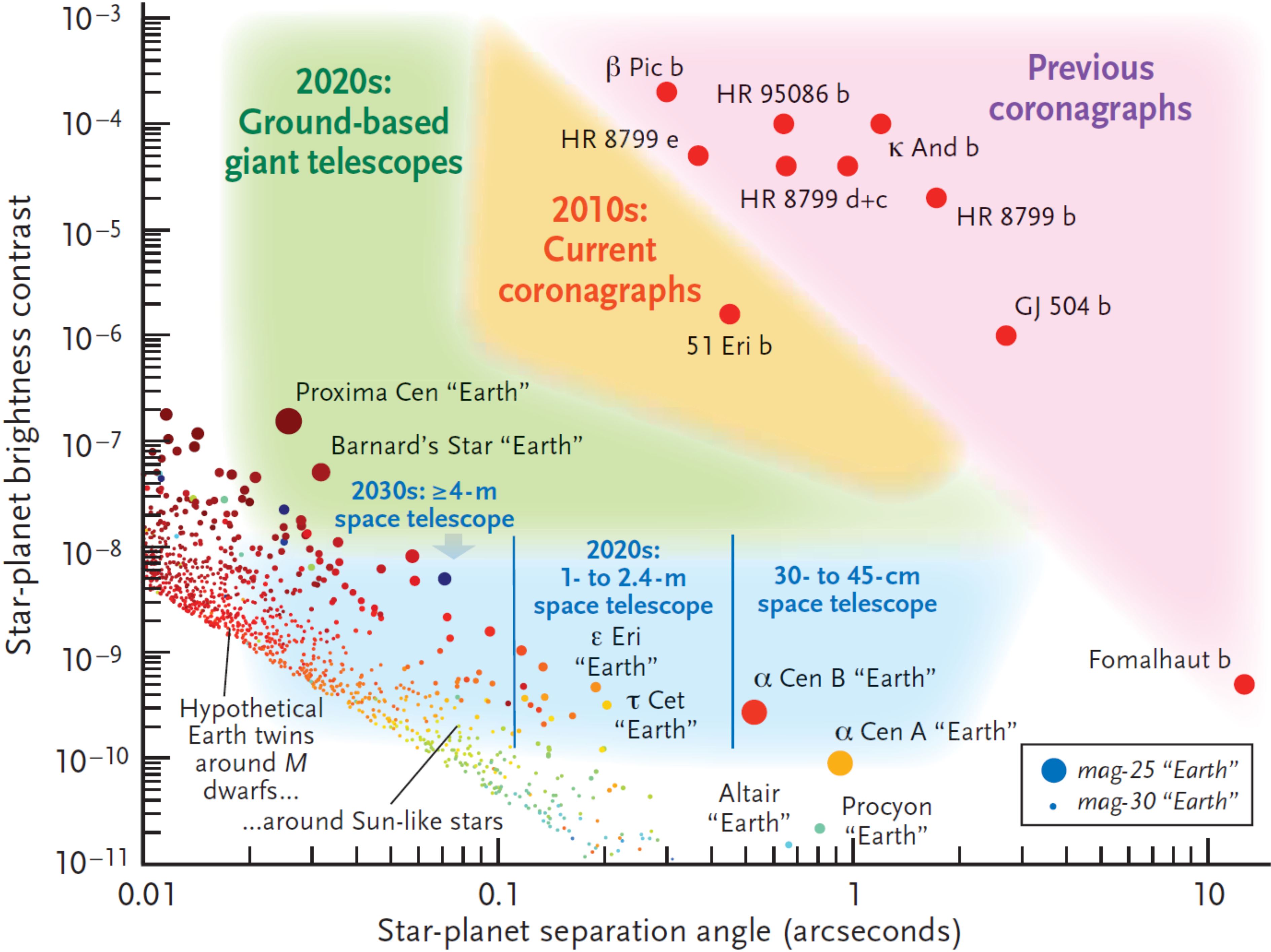
- 517 FGK stars within 20pc
- 259 multi-stars (optical or dynamical)
- 193 stars limited at > 1e-10
  - 40 stars with sep. < N/2 λ/D

HabEx assumptions:

- D = 4m
- λ = 650nm
- λ/20 RMS with f^{-3} power spectrum
- 48x48 DM

Note: Contrast floor for an on-axis coronagraph/starshade due to unsuppressed off-axis companion star

Sirbu



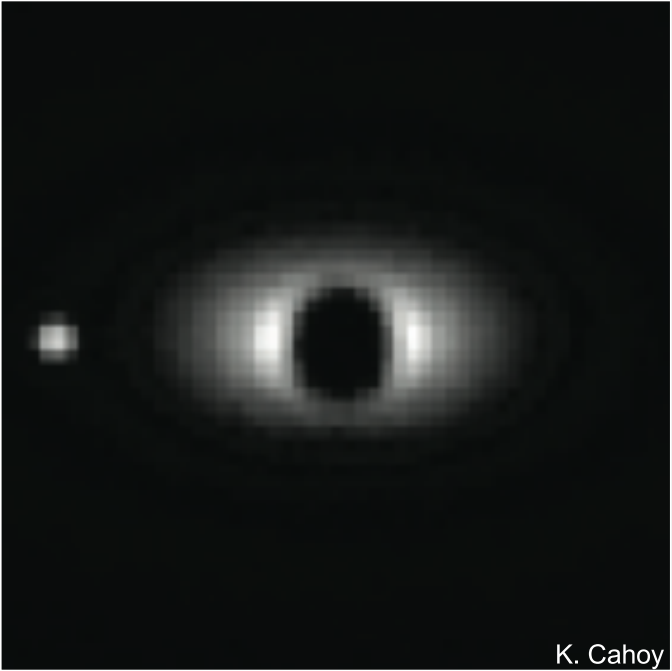
R. BELIKOV / E. BENDEK / O. GUYON

Sky and Telescope, Oct 2015

Alpha Centauri: not your typical target

Simulations of an Earth twin detection for a ~1.5 class telescope
(similar to Exo-C, Exo-S)

α Cen (A)



1.5m aperture, 1 hour exposure

nothing
in-between

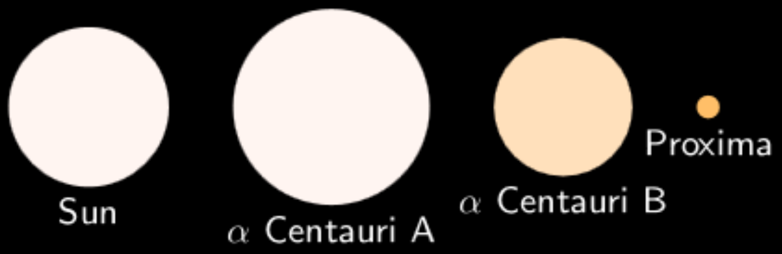
←→

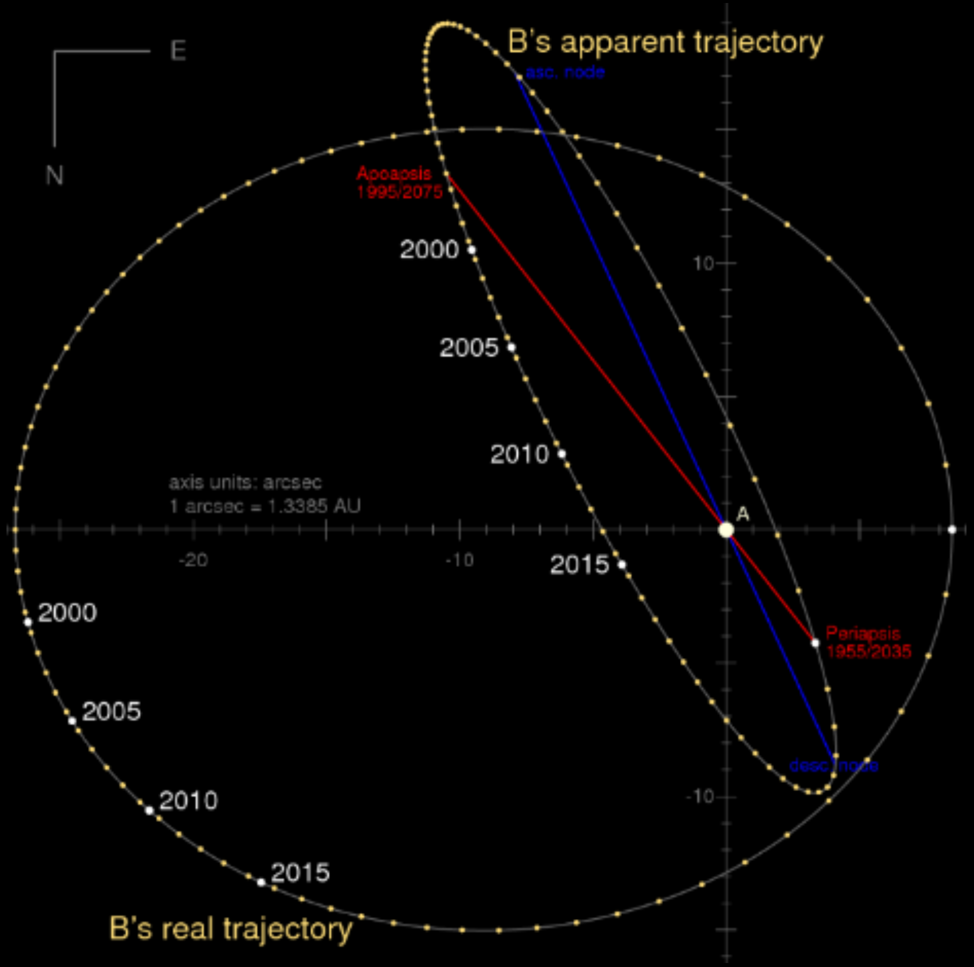
τ Cet (~ best of everything else)

1.5m aperture, 1 hour exposure

If Alpha Centauri was not a binary, it would probably be the best target for any direct imaging mission, by a large margin

α Cen System Overview





Habitable Zones of αCen AB

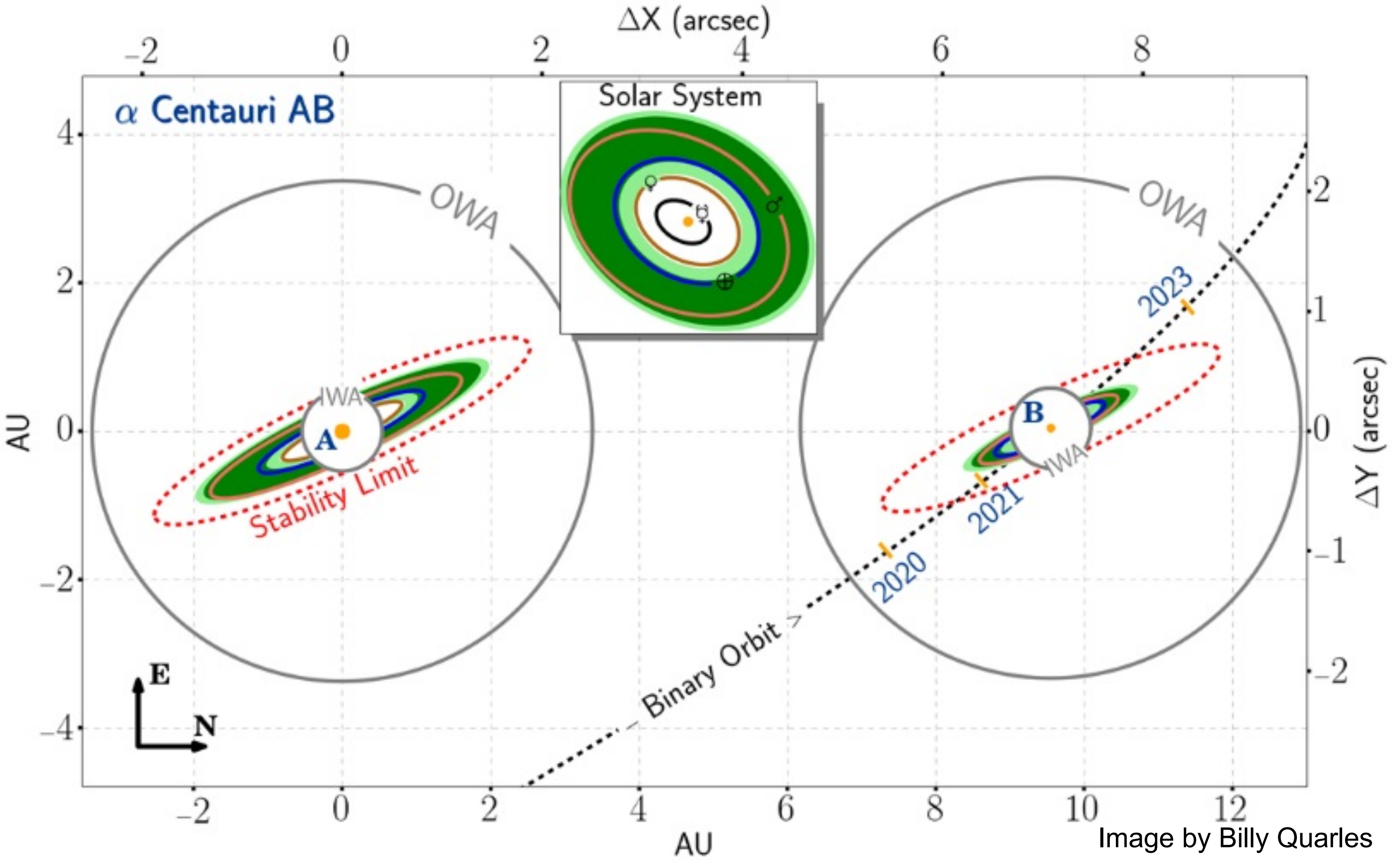


Image by Billy Quarles

see Quarles and Lissauer 2016 for aCen stability
https://arxiv.org/abs/1604.04917

- Both HZs are fully accessible with a 0.4” (0.5AU) inner working angle (IWA)
- Orbits are stable out to ~ 2.5 AU (Holman & Wiegert 1999, Quarles and Lissauer 2016)

ACESat: Alpha Centauri Exoplanet Satellite

ACESat:
Alpha Centauri Exoplanet Satellite
Exploring the nearest star system for habitable worlds

A mission capable of directly imaging an Earth-like planet in the nearest star system

Signature goes here
Dr. S. Pete Worden
Director
NASA Ames Research Center

Signature goes here
Dr. Ruslan Belikov
Principal Investigator
NASA Ames Research Center

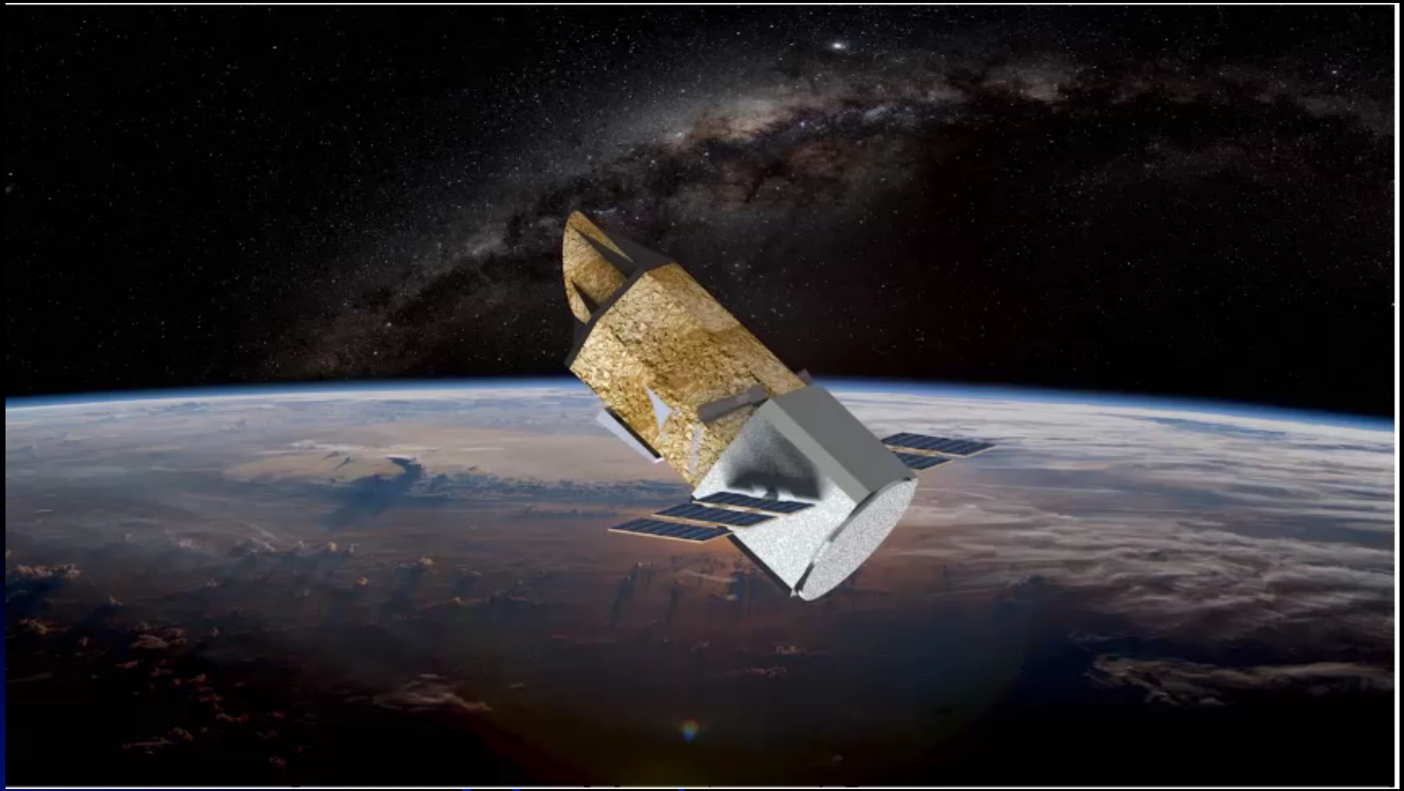
2014 Astrophysics SMEX, Solicitation #NNH14ZDA013O

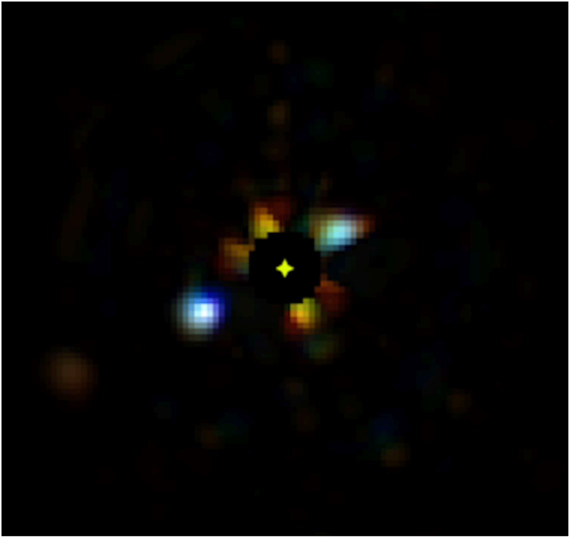
Mission Time Life and Orbit	SMEX-Class, launch 2020, 2-Years, Earth trailing
Instrument/ Telescope	Unobstructed 45cm, Full Silicon Carbide
Coronagraph architecture	Baseline: PIAA Embedded on Secondary and tertiary telescope mirror.
Coronagraph performance	$1x10^{-8}$ raw $6x10^{-11}$ @ 0.4” (with ODI) $2x10^{-11}$ @ 0.7” (with ODI)
Wavelength	400 to 700 nm, 5 bands @ 10% each.

proposed to SMEX, 2014

Belikov, R. (PI),
Bendek, E. (DPI)
Batalha, N.
Kuchner, M.
Lissauer, J.
Males, J.
Marley, M.
Quarles, B.
Quintana, E.
Robinson, T.
Schneider, G.
Traub, W.
Turnbull, M.
Chakrabarti, S.
Guyon, O.
Kasdin, J.
Lozi, J.
McElwain, M.
Pluzhnik, E.
Thomas, S.
Vanderbei, B.
et al.

Project Blue





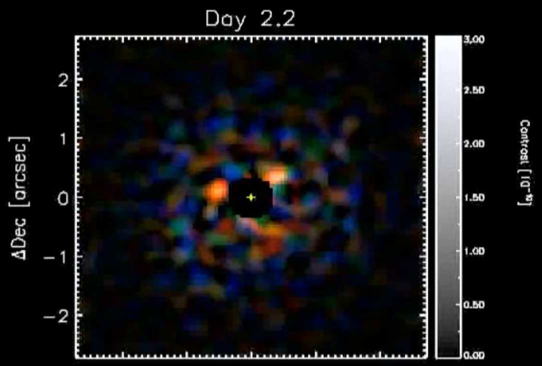
BoldlyGo

SETI Institute

UMass Lowell

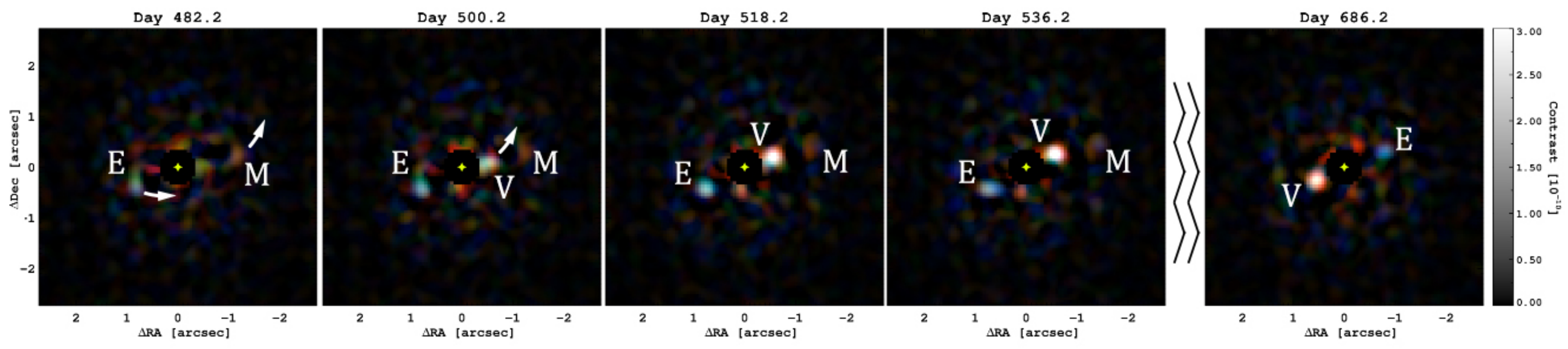
Mission Centaur

ACESat data simulation

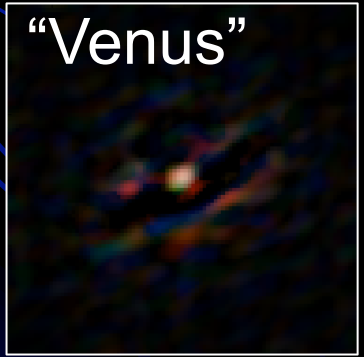


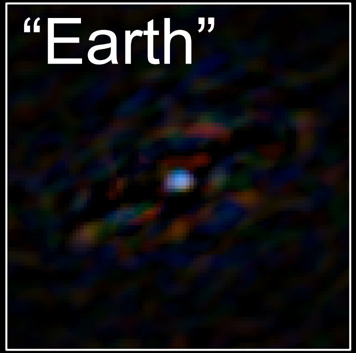
- Simulation parameters (ACESat mission)
  - D = 45cm
  - PIAA coronagraph
  - 1e-8 starting contrast (assumed after MSWC)
  - 0.5mas (1σ rms) random tip/tilt jitter
  - 5 color filters
  - 2-year mission
  - Photon noise included (dominates over read)

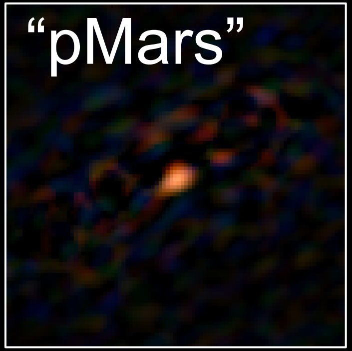
After filtering:



After shift-and-add

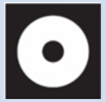
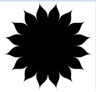
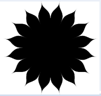
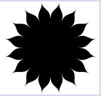
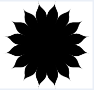
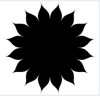






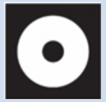
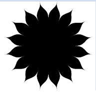
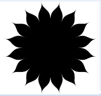
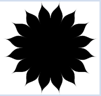
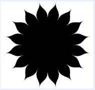
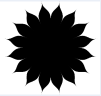
Note: "pMars" is larger
but farther away than
Solar Mars

*Assuming DM = NxN actuators

SCENARIO		WC SOLUTIONS		
On-axis blocker	**Off-axis blocker**	**Star Separation at < N/2 λ/D***	**Star Separation at > N/2 λ/D***	**Notes**
Coronagraph 	None (WC only)	**MSWC-0**	**MSWC-s**	**Existing coronagraphic mission concepts are already capable** of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane.
Coronagraph 	2nd Coronagraph 	**MSWC-0**	**MSWC-s**	**The second (off-axis) coronagraph would require an additional mask.** It can be helpful if diffraction rings from the off-axis star are significant. MSWC is still required if wavefront error is significant.
Coronagraph 	Starshade 	SSWC (i.e. standard WC)	SSWC (i.e. standard WC)	Adding a starshade effectively **reduces binaries to single-star** suppression problem, at a **cost of adding a starshade**
Starshade 	None (WC only)	SSWC (i.e. standard WC)	**SNWC**	**Adding a deformable mirror** (without a coronagraph) to a starshade mission theoretically **enables double-star suppression**
Starshade 	Coronagraph 	SSWC (i.e. standard WC)	**SNWC**	**The off-axis coronagraph is not necessary** for a well-baffled telescope, but may relax the stroke requirement on the DM for close stars
Starshade 	2nd Starshade 	No WC required	No WC required	Adding a starshade for the off-axis star effectively **reduces binaries to single-star** suppression problem, but at a **cost of adding a second starshade**

SSWC=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, MSWC-0 = Multi-Star WC (0th order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)

*Assuming DM = NxN actuators

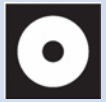
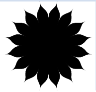
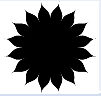
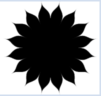
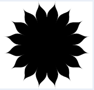
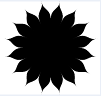
SCENARIO		WC SOLUTIONS		
On-axis blocker	**Off-axis blocker**	**Star Separation at < N/2 λ/D***	**Star Separation at > N/2 λ/D***	**Notes**
Coronagraph 	None (WC only)	**MSWC-0**	**MSWC-s**	**Existing coronagraphic mission concepts are already capable** of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane.
Coronagraph 	2nd Coronagraph 	**MSWC-0**	**MSWC-s**	**The second (off-axis) coronagraph would require an additional mask.** It can be helpful if diffraction rings from the off-axis star are significant. MSWC is still required if wavefront error is significant.
Coronagraph 	Starshade 	SSWC (i.e. standard WC)	SSWC (i.e. standard WC)	Adding a starshade effectively **reduces binaries to single-star** suppression problem, at a **cost of adding a starshade**
Starshade 	None (WC only)	SSWC (i.e. standard WC)	**SNWC**	**Adding a deformable mirror** (without a coronagraph) to a starshade mission theoretically **enables double-star suppression**
Starshade 	Coronagraph 	SSWC (i.e. standard WC)	**SNWC**	**The off-axis coronagraph is not necessary** for a well-baffled telescope, but may relax the stroke requirement on the DM for close stars
Starshade 	2nd Starshade 	No WC required	No WC required	Adding a starshade for the off-axis star effectively **reduces binaries to single-star** suppression problem, but at a **cost of adding a second starshade**

SSWC=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, MSWC-0 = Multi-Star WC (0th order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)

SCENARIO

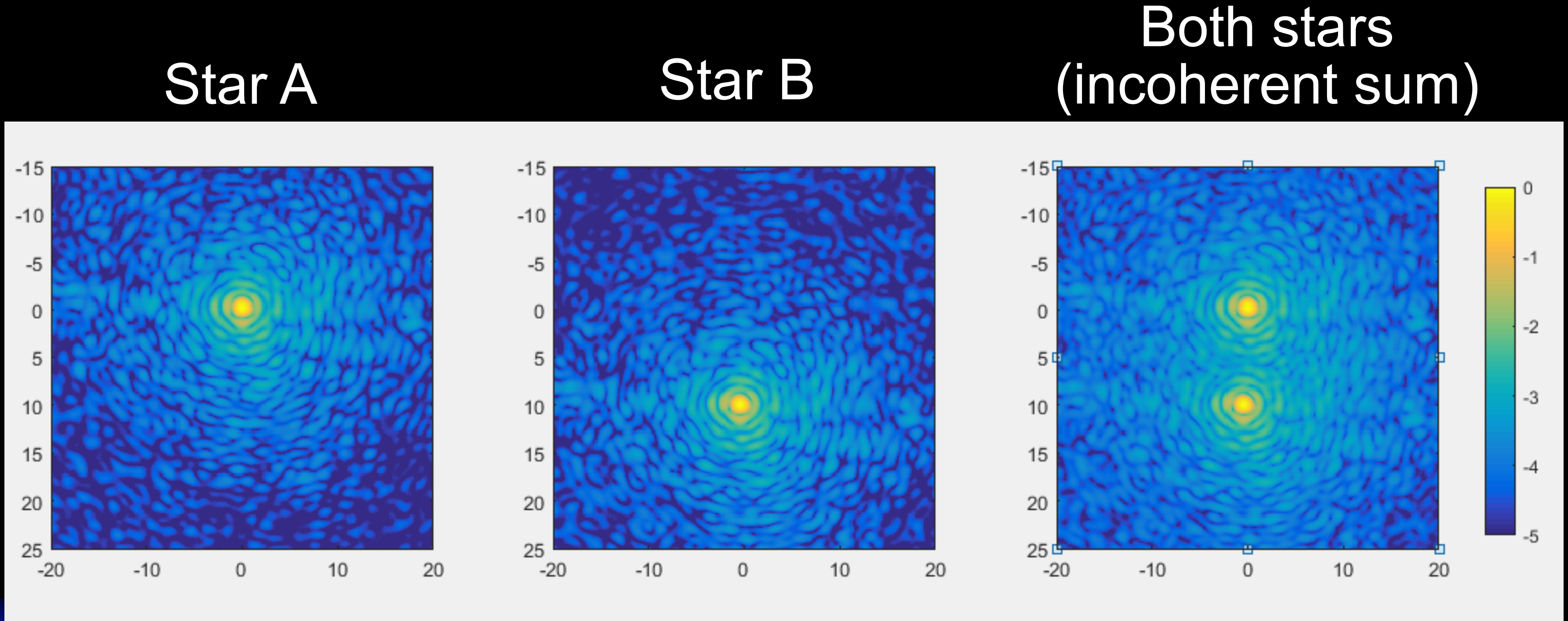
WC SOLUTIONS

*Assuming DM = NxN actuators

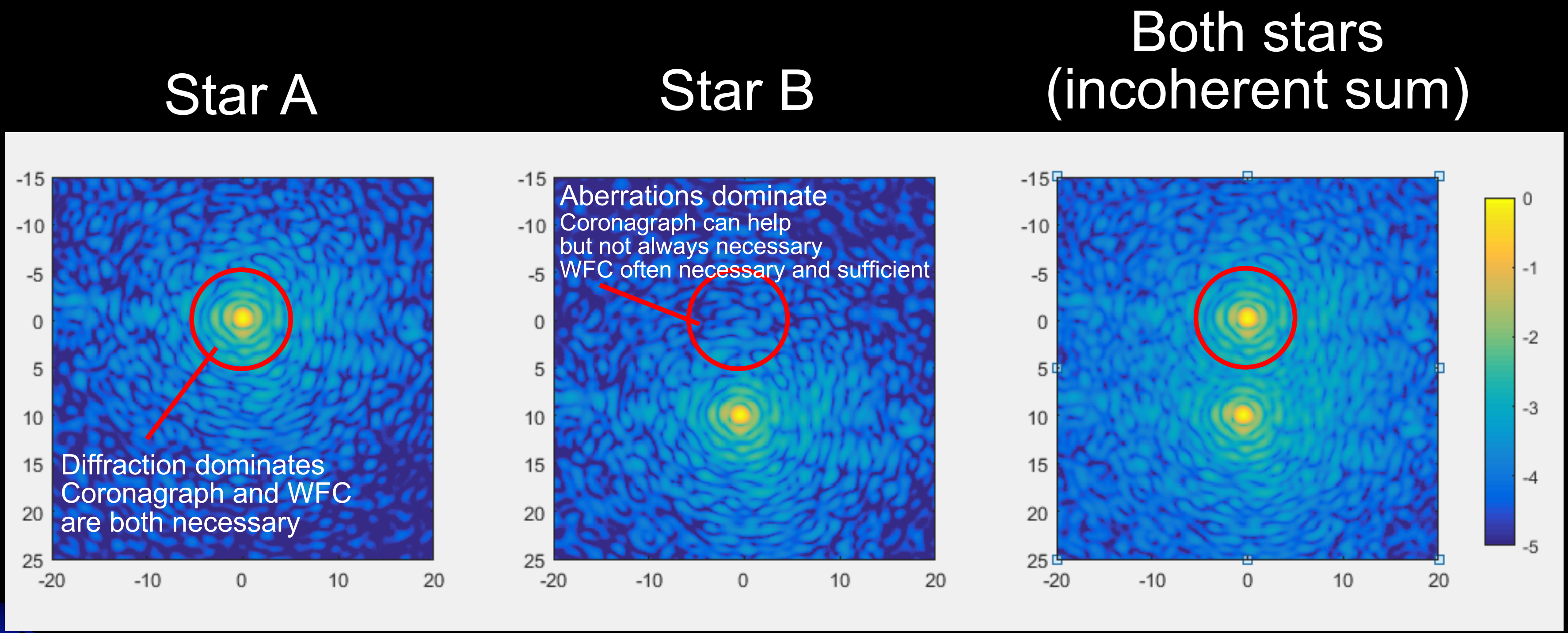
On-axis blocker	Off-axis blocker	Star Separation at < N/2 λ/D*	Star Separation at > N/2 λ/D*	Notes
Coronagraph 	None (WC only)	**MSWC-0**	**MSWC-s**	**Existing coronagraphic mission concepts are already capable** of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane
Coronagraph 	2nd Coronagraph 	**MSWC-0**	**MSWC-s**	**The second (off-axis) coronagraph would require an additional mask.** It can be helpful if diffraction rings from the off-axis star are significant. MSWC is still required if wavefront error is significant.
Coronagraph 	Starshade 	SSWC (i.e. standard WC)	SSWC (i.e. standard WC)	Adding a starshade effectively **reduces binaries to single-star** suppression problem, at a **cost of adding a starshade**
Starshade 	None (WC only)	SSWC (i.e. standard WC)	**SNWC**	**Adding a deformable mirror** (without a coronagraph) to a starshade mission theoretically **enables double-star suppression**
Starshade 	Coronagraph 	SSWC (i.e. standard WC)	**SNWC**	**The off-axis coronagraph is not necessary** for a well-baffled telescope, but may relax the stroke requirement on the DM for close stars
Starshade 	2nd Starshade 	No WC required	No WC required	Adding a starshade for the off-axis star effectively **reduces binaries to single-star** suppression problem, but at a **cost of adding a second starshade**

SSWC=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, MSWC-0 = Multi-Star WC (0th order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)

Challenges in coronagraphic multi-star high contrast imaging



Challenges in coronagraphic multi-star high contrast imaging



Star A

Star B

Both stars (incoherent sum)

Diffraction dominates
Coronagraph and WFC
are both necessary

Aberrations dominate
Coronagraph can help
but not always necessary
WFC often necessary and sufficient

- Second coronagraph helps, but if aberrations from the second star are significant, active suppression (wavefront control) of both stars is required
  - Speckles from the two stars are mutually incoherent and must be suppressed independently
- Wavefront control of second star may be sufficient to suppress it
  - DM effectively acts as a phase mask coronagraph on the second star, in addition to active speckle correction.
  - All direct imaging missions being designed right now are potentially capable of multi-star high contrast imaging
  - Multi-star coronagraph can still help of course and under some conditions may be sufficient (AJ Riggs)
    - Especially to help with blooming / pixel cross-talk due to 2nd star

How to Block 2nd Star? (work by AJ Riggs)

Option 1: Simple Starshade

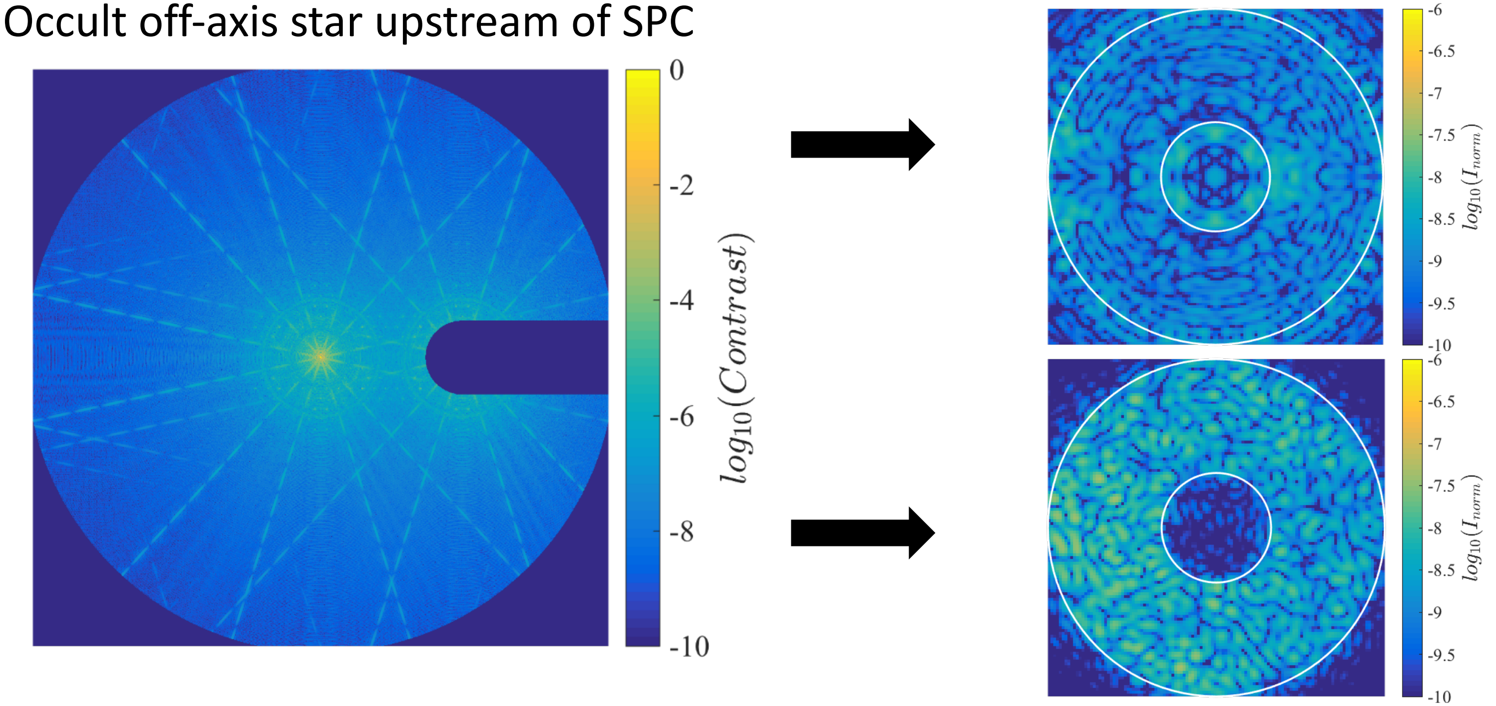
- Low contrast: Only ~10^{-4} needed
- Small: 5m-10m diameter fine.

➢ Inexpensive

~2.5 hours for SNR=5 at 10^{-10} contrast for α Cen A & B

Option 2: Extra Mask inside WFIRST CGI

Occult off-axis star upstream of SPC

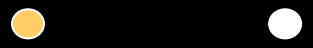


<=1 x 10-9
from
on-axis star

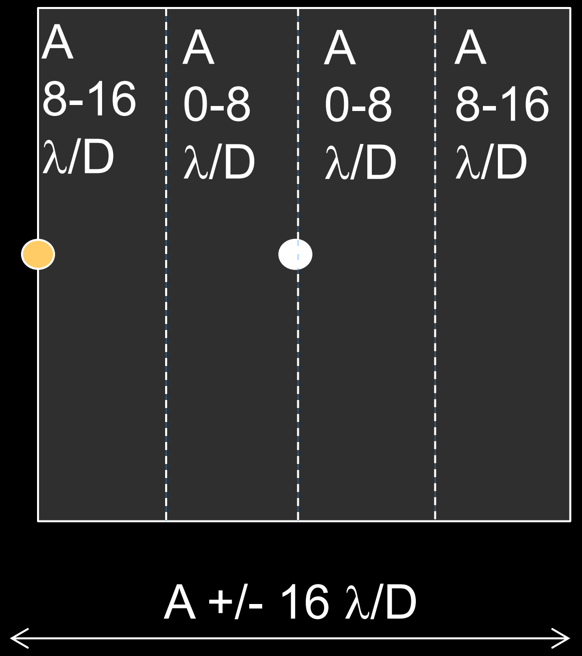
5-10 x 10-9
from
off-axis star

<=1 day to get SNR=5 at 10^{-10} contrast for α Cen A

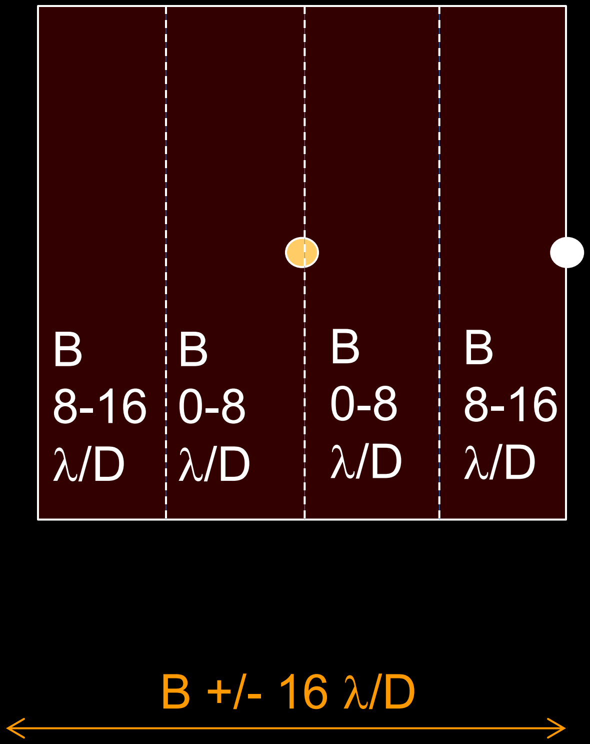
Multi-Star Wavefront Control



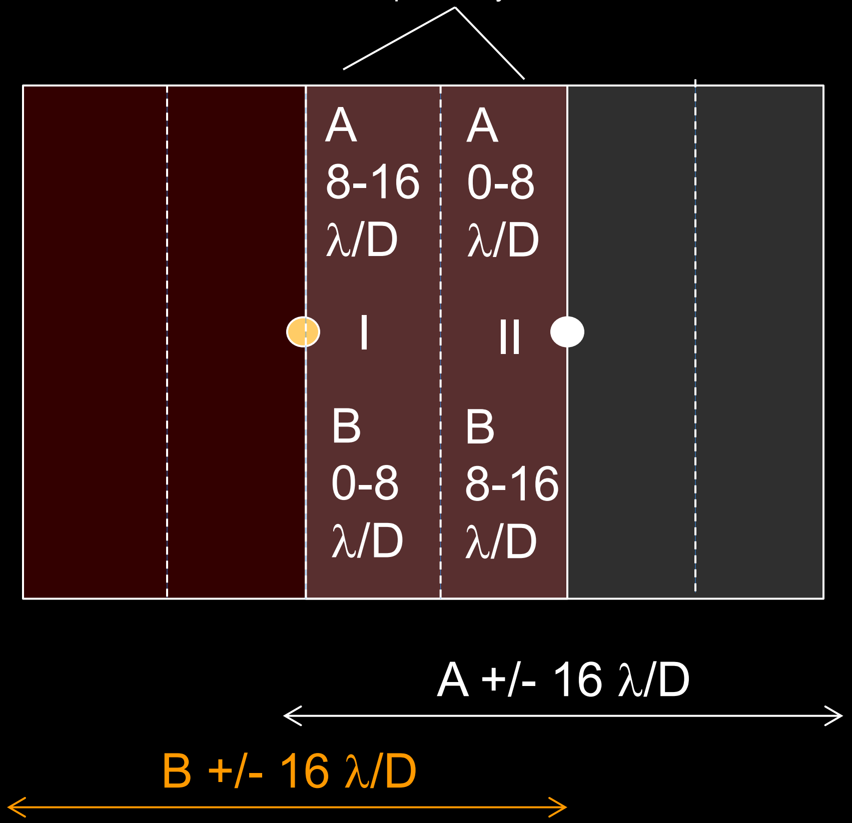
Multi-Star Wavefront Control



Multi-Star Wavefront Control



Multi-Star Wavefront Control



In these regions, independent DM modes are used for the two stars and therefore speckles from the two stars can be independently controlled

MSWC-0 generalization of EFC

Single star-EFC (monochromatic) Solve:

$$G\bar{a} = -E_{\mathrm{ab}}$$

n-star MSWC-0 (monochromatic) Solve:

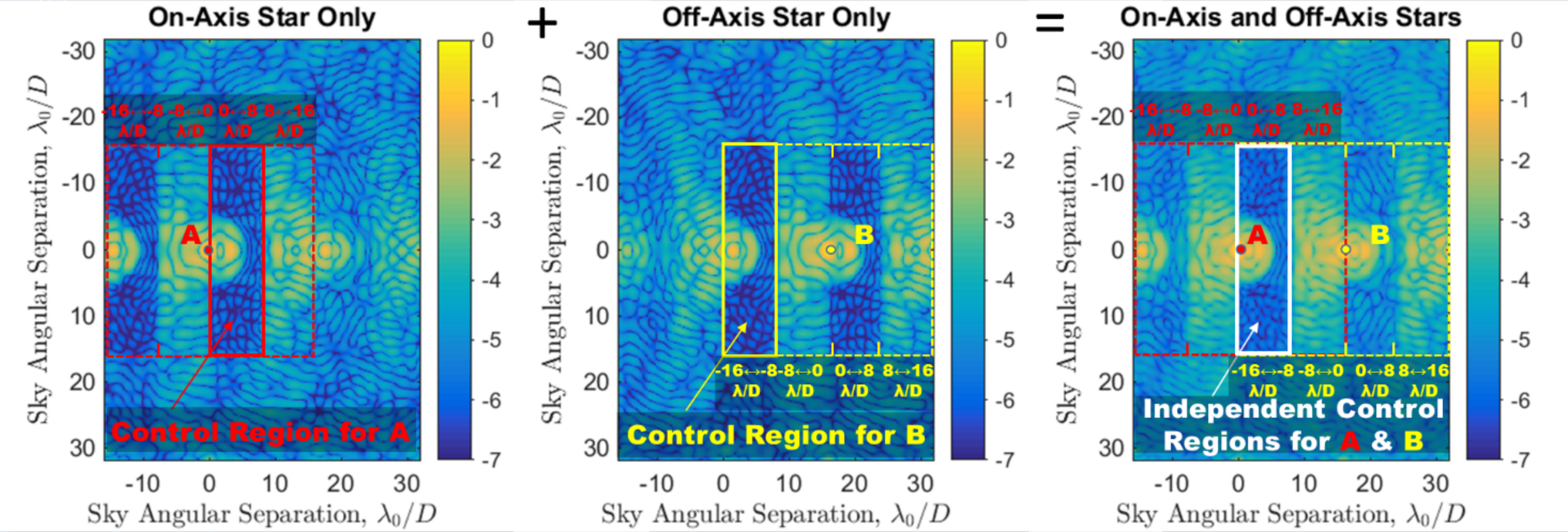
$$n\text{ stars}\left\{\begin{bmatrix} G_1 \\ \vdots \\ G_n \end{bmatrix}\right. \bar{a} = -\begin{bmatrix} E_{\mathrm{ab},1} \\ \vdots \\ E_{\mathrm{ab,n}} \end{bmatrix}$$

n-star broadband MSWC-0 Solve:

$$\begin{bmatrix} G_1(\lambda_1) \\ G_1(\lambda_2) \\ G_1(\lambda_3) \\ G_2(\lambda_1) \\ G_2(\lambda_2) \\ G_2(\lambda_3) \end{bmatrix} \bar{a} = -\begin{bmatrix} E_{\mathrm{ab},1}(\lambda_1) \\ E_{\mathrm{ab},1}(\lambda_2) \\ E_{\mathrm{ab},1}(\lambda_3) \\ E_{\mathrm{ab},2}(\lambda_1) \\ E_{\mathrm{ab},2}(\lambda_2) \\ E_{\mathrm{ab},2}(\lambda_3) \end{bmatrix}$$

E: array of electric field values at CCD pixels (flattened into a vector)
a: DM actuator coefficients
G: Matrix representing the instrument, relating DM actuator coefficients to EFs

Multi-Star Wavefront Control: main principle

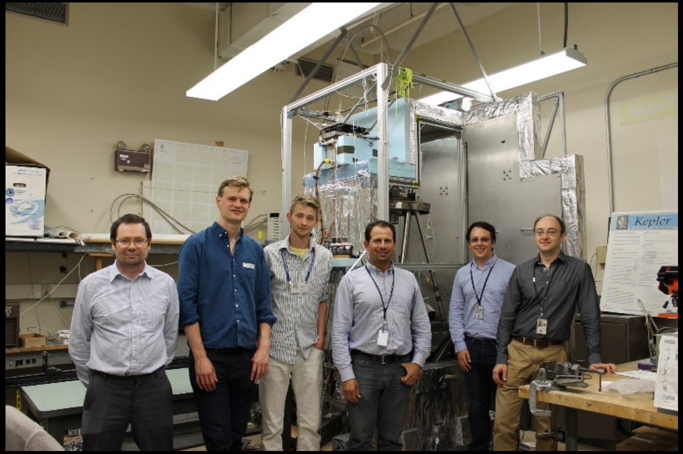


Simulation by D. Sirbu

- Main idea: use different DM modes for star A and star B
  - Note: complete separation is impossible due to second-order effects, but these effects can be ignored in closed loop
- Requires a “non-redundant” dark zone, i.e. a zone where DM modes used for A star do not overlap with those used for B
- Corollaries:
  - 2-star problem is reduced to 2 simultaneous 1-star problems. Can be solved by
    - “stacking” the G-matrixes for A and B, and using standard EFC
    - interlacing A and B iterations with standard EFC or speckle nulling
  - Area of dark zone is ½ of the single star case
- Everything generalizes to N stars, but dark zone shrinks by a factor of 1/N

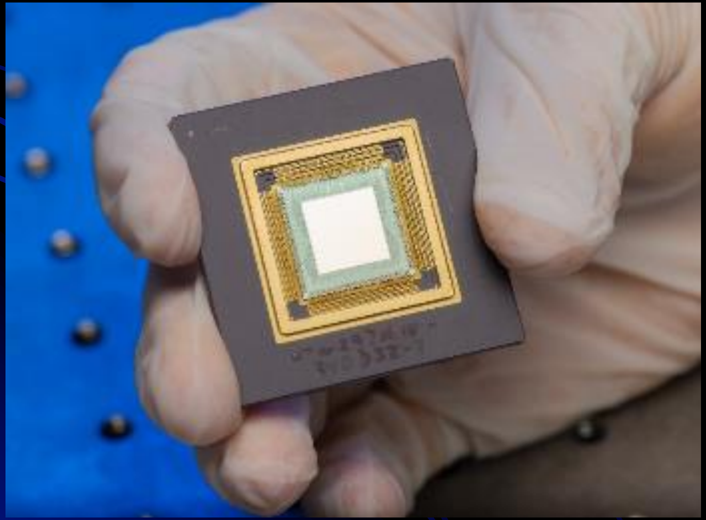
Ames Coronagraph Experiment (ACE) Laboratory

Team

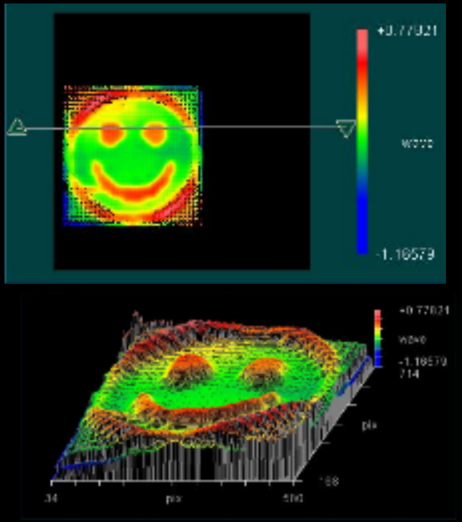


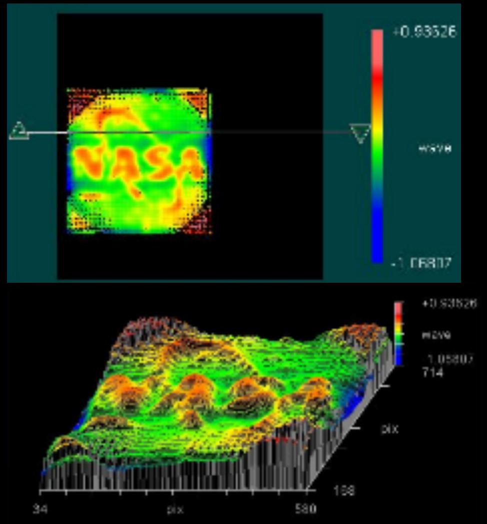
Two thermally stabilized testbeds

BMC DM: 32 x 32 actuators



(see Bendek et al. 2016 for a new compact DM driver)



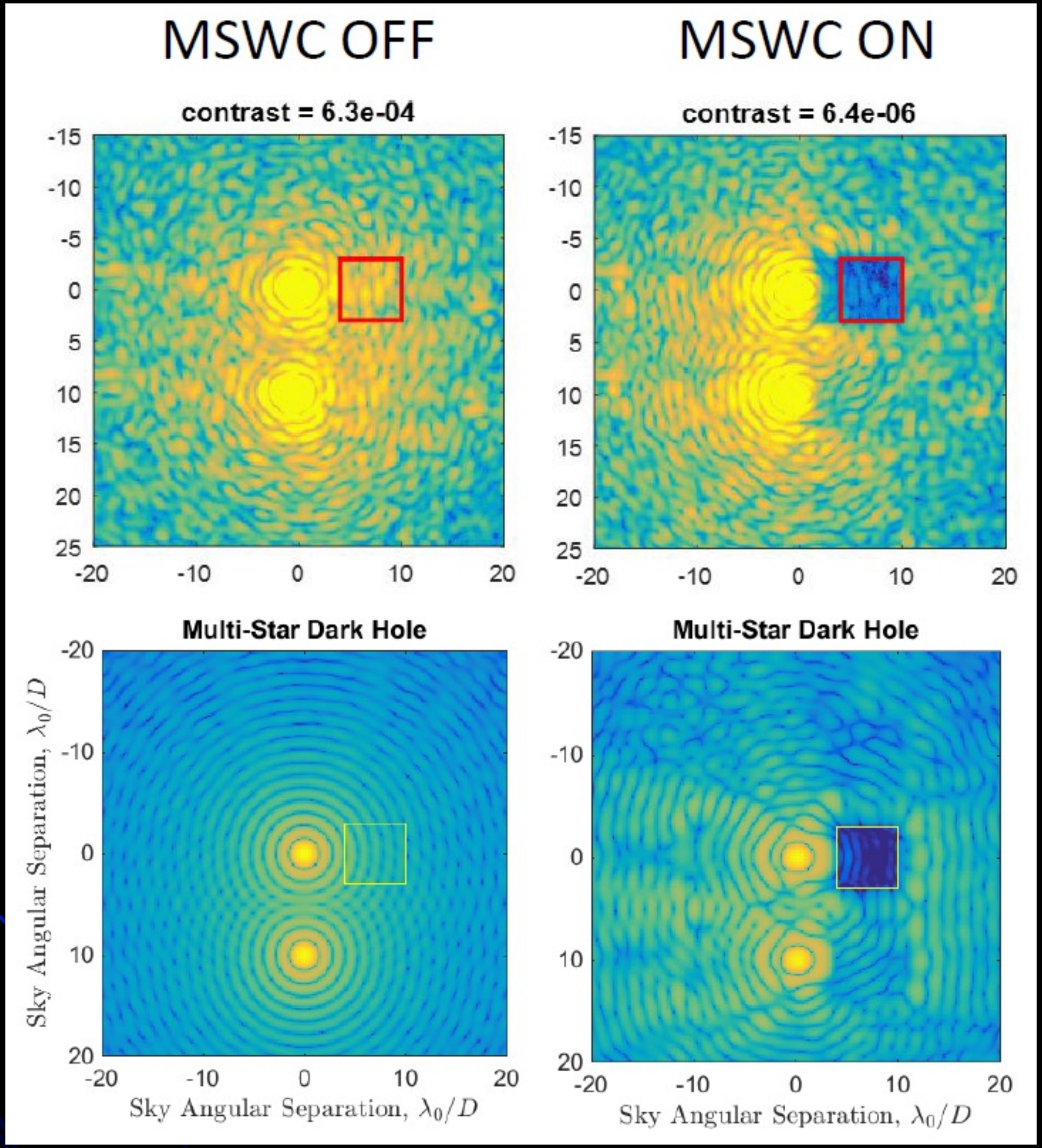


Lab tests of MSWC-0

(for now, without coronagraph)

Lab images
(Pluzhnik)

Simulation
(Sirbu)



655nm light

No coronagraph (for simplicity)

10 λ/D star separation

Equal brightness

Belikov et al. 2016

Lab tests of MSWC-0

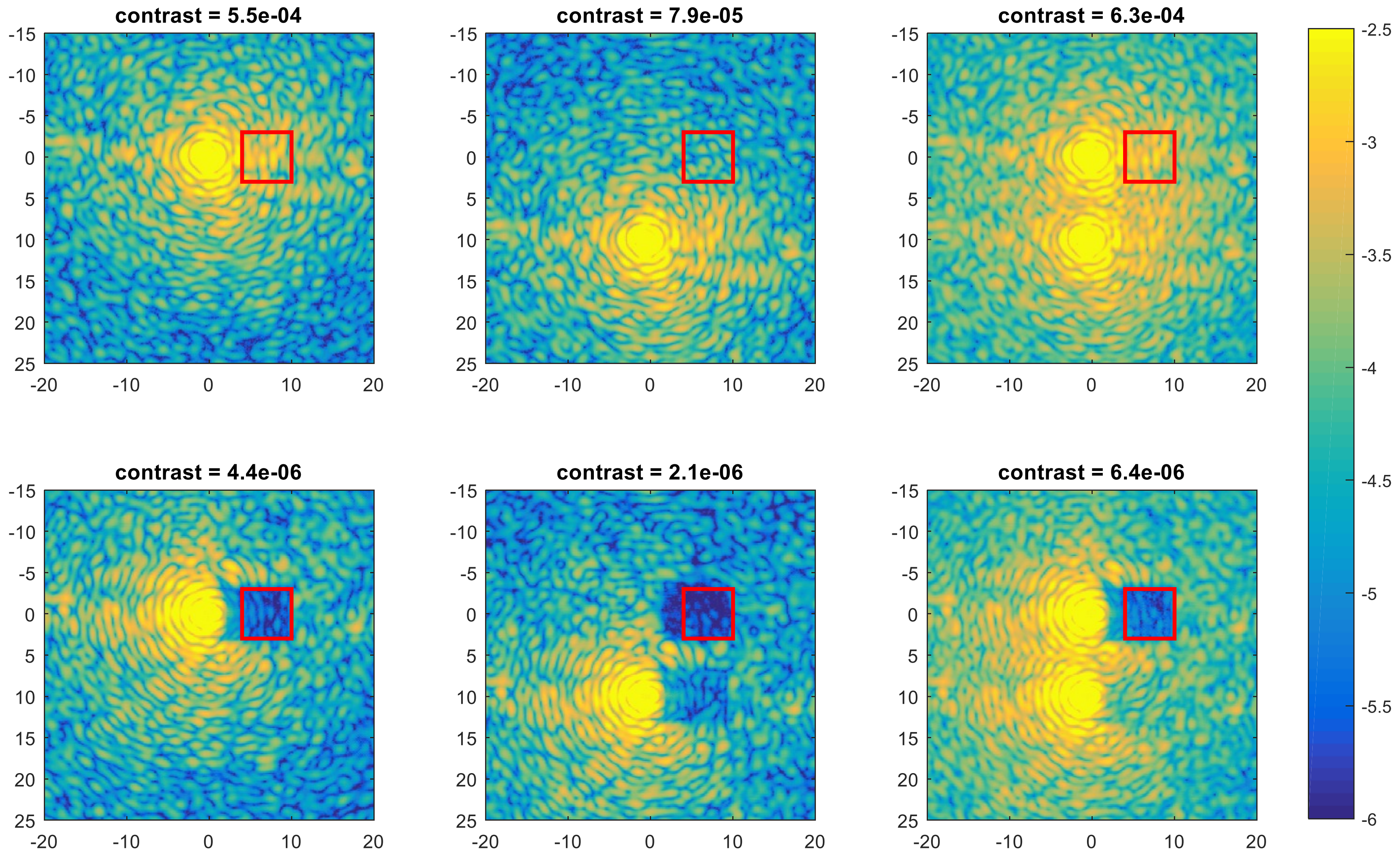
star A

star B

both stars

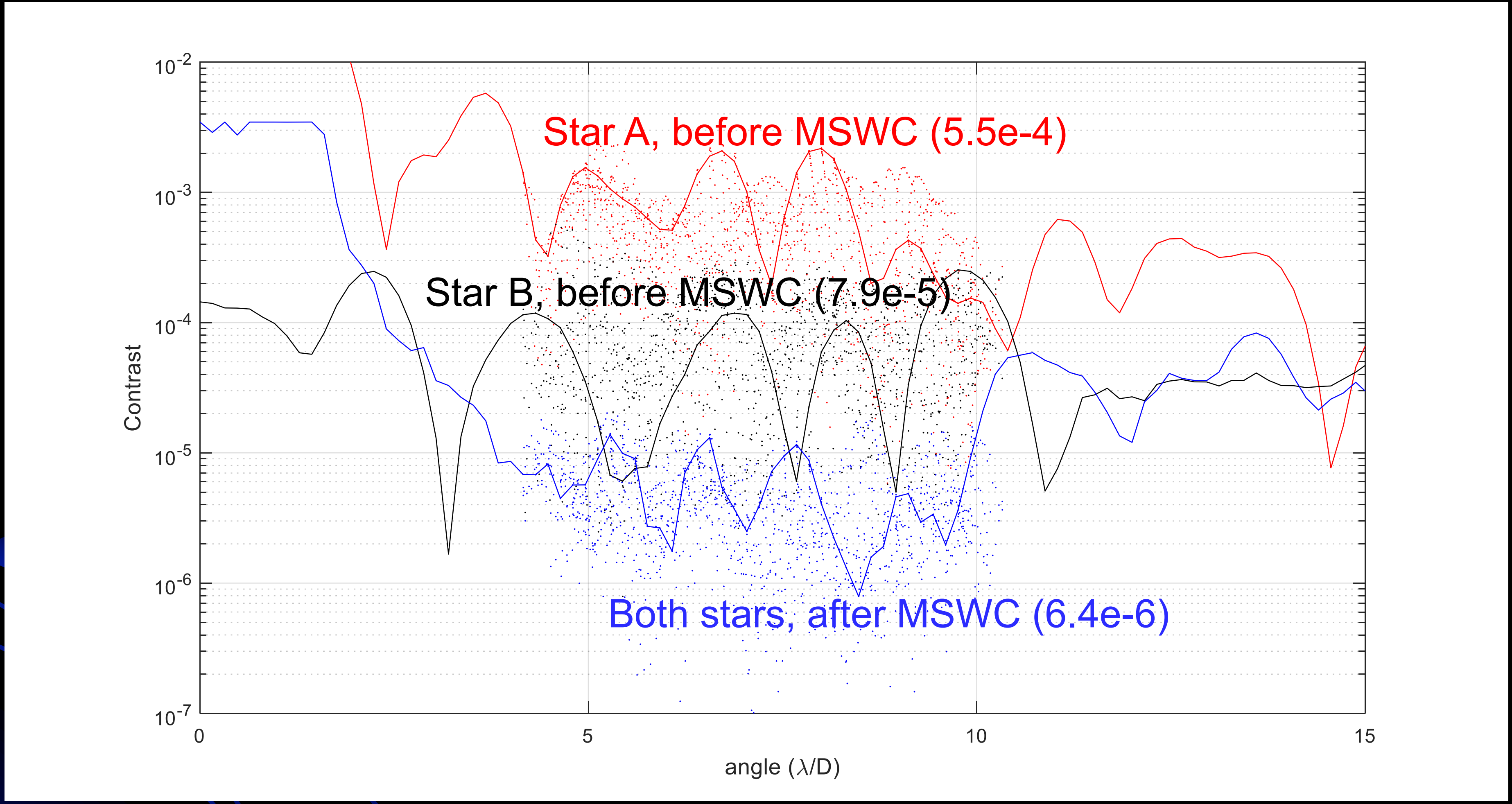
Before MSWC

After MSWC
(all images: same DM setting)



WFC run by Eugene Pluzhnik

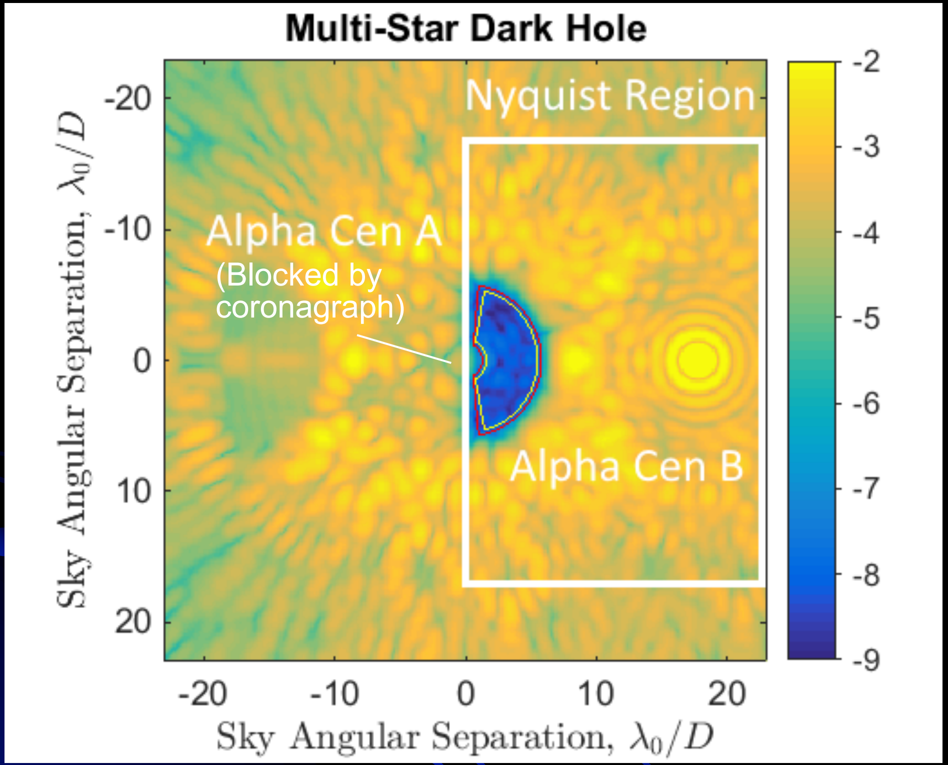
Horizontal slices



Multi-Star Wavefront Control broadband simulations. 10% @ 650nm

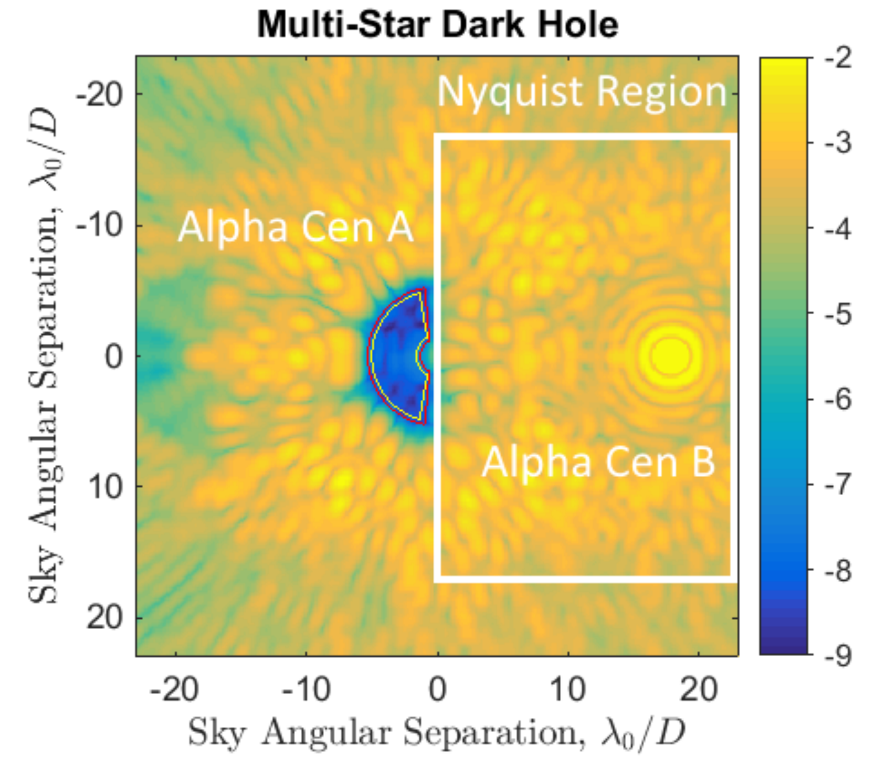
Mean contrast: ***8.3 x 10^{-9}***

Multi-Star Wavefront Control



Mean contrast: ***8.4 x 10^{-8}***

Super-Nyquist Multi-Star Wavefront Control



10% @ 650nm

0.35m aperture

PIAA coronagraph

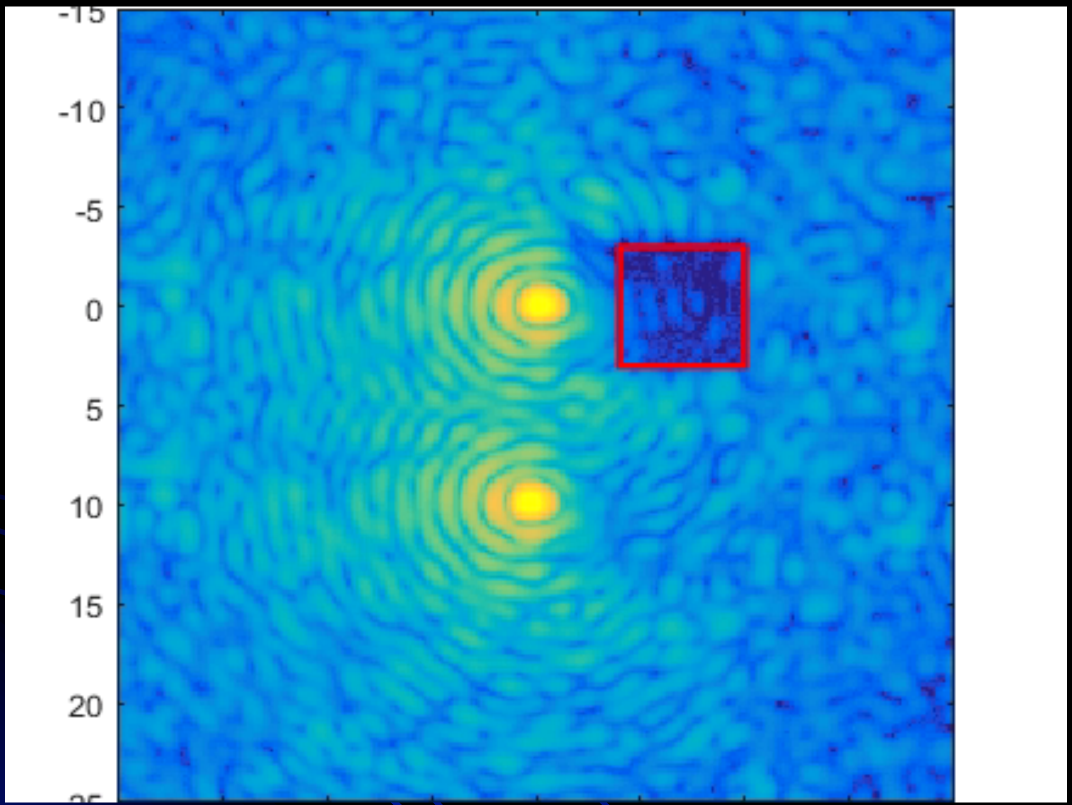
32 x 32 actuator DM

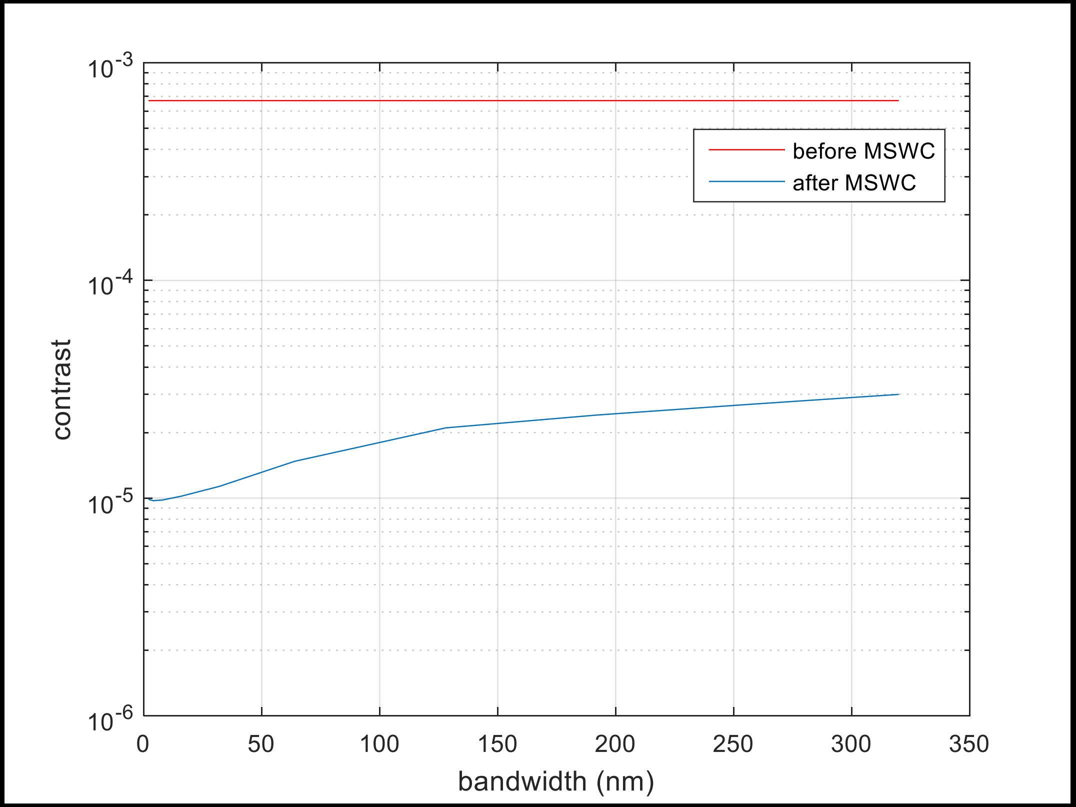
(Sirbu et al. 2017, submitted to ApJ)

- Coronagraph for second star is neither sufficient nor necessary!
- MSWC works by using different independent DM spatial modes for each star
- No hardware change is required for MSWC – should work for any mission with a DM (WFIRST, LUVOIR, HabEx)
  - SNMSWC needs a DM with a quilting (print-through) pattern or other grating

Preliminary broadband test (MSWC-0)

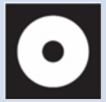
Scanning from 0 to 50% band





SCENARIO WC SOLUTIONS

*Assuming DM = NxN actuators

On-axis blocker	Off-axis blocker	Star Separation at < N/2 λ/D*	Star Separation at > N/2 λ/D*	Notes
Coronagraph 	None (WC only)	**MSWC-0**	**MSWC-s**	**Existing coronagraphic mission concepts are already capable** of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane
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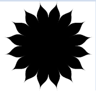
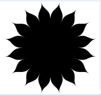
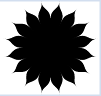
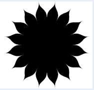
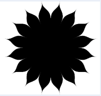
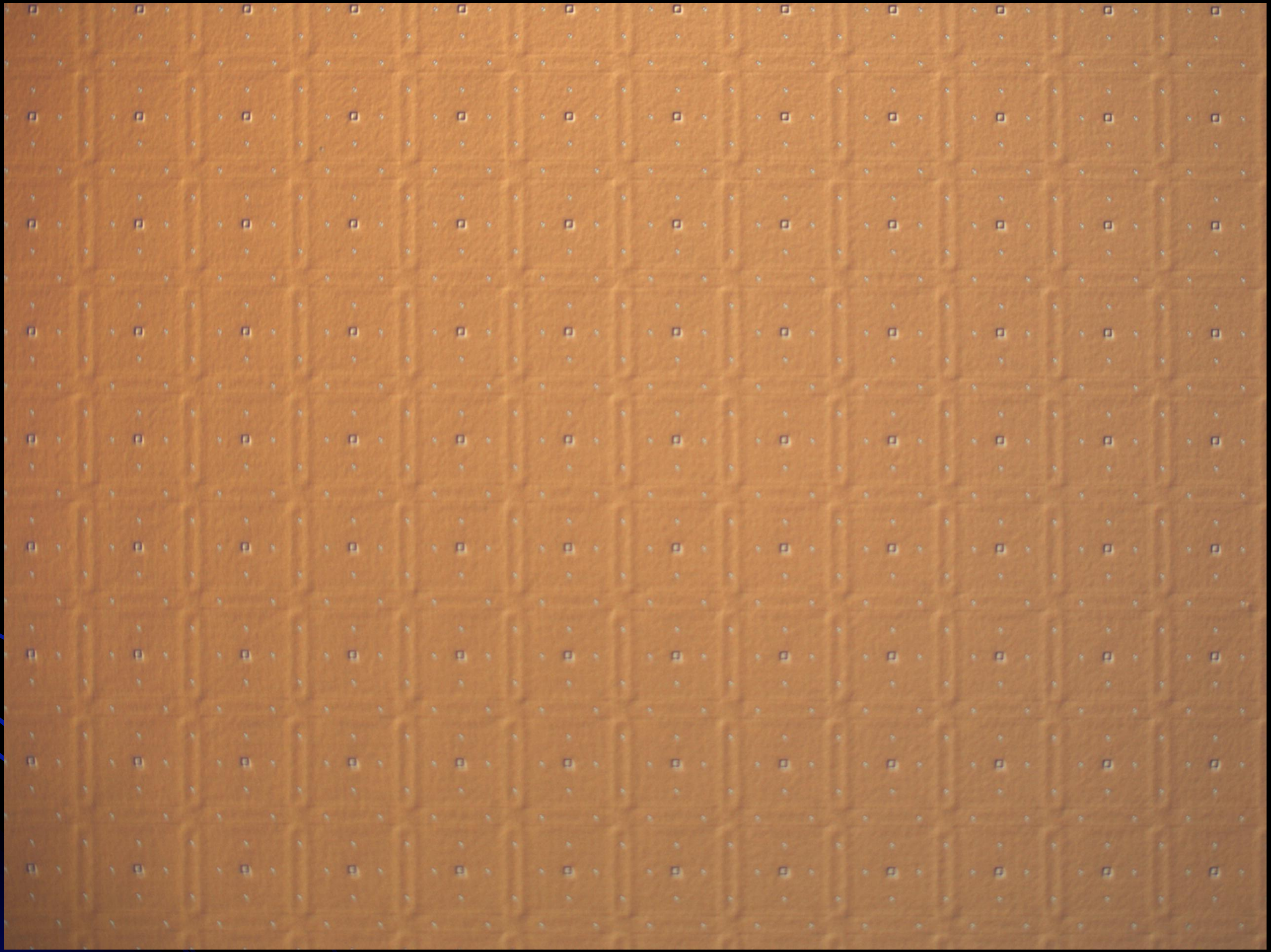
Coronagraph 	Starshade 	SSWC (i.e. standard WC)	SSWC (i.e. standard WC)	Adding a starshade effectively **reduces binaries to single-star** suppression problem, at a **cost of adding a starshade**
Starshade 	None (WC only)	SSWC (i.e. standard WC)	**SNWC**	**Adding a deformable mirror** (without a coronagraph) to a starshade mission theoretically **enables double-star suppression**
Starshade 	Coronagraph 	SSWC (i.e. standard WC)	**SNWC**	**The off-axis coronagraph is not necessary** for a well-baffled telescope, but may relax the stroke requirement on the DM for close stars
Starshade 	2nd Starshade 	No WC required	No WC required	Adding a starshade for the off-axis star effectively **reduces binaries to single-star** suppression problem, but at a **cost of adding a second starshade**

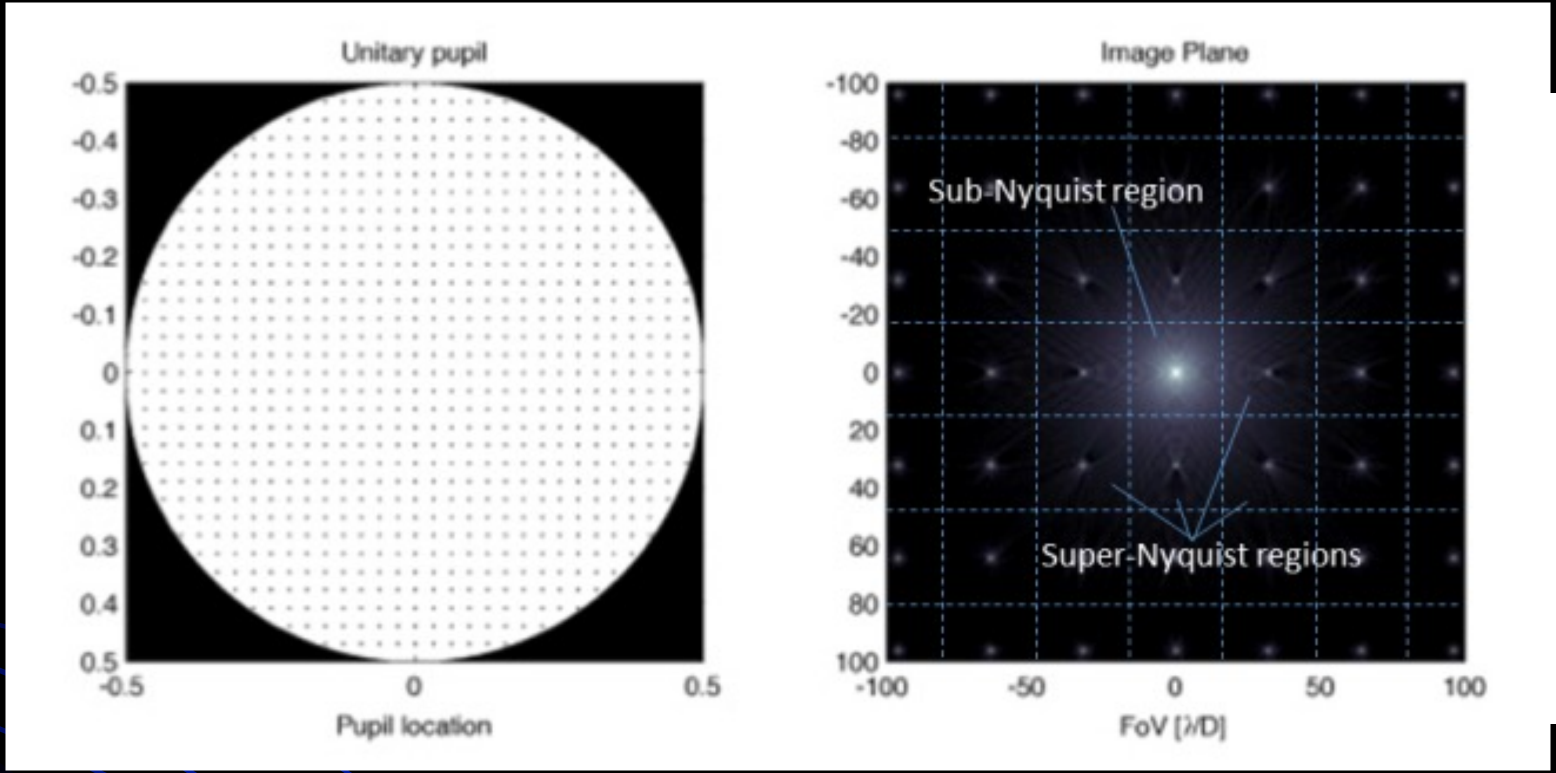
SSWC=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, MSWC-0 = Multi-Star WC (0^{th} order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)

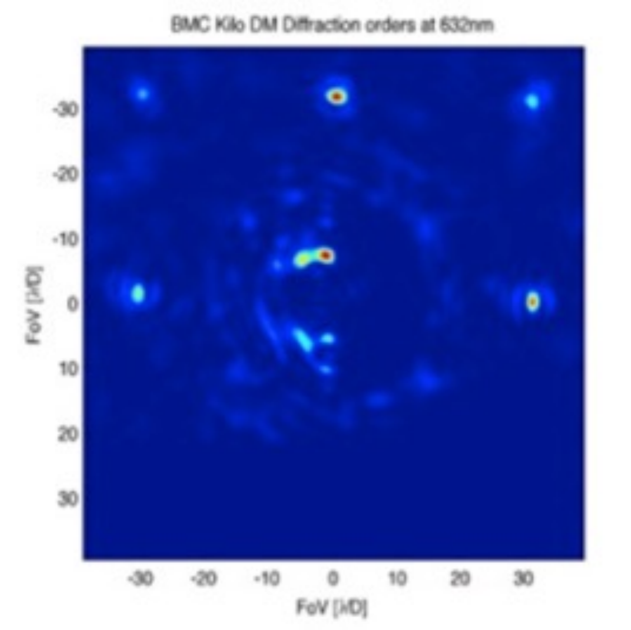
DM “quilting”: a feature, not a bug



Phase microscope image of a BMC deformable mirror surface

Super-Nyquist WC principle

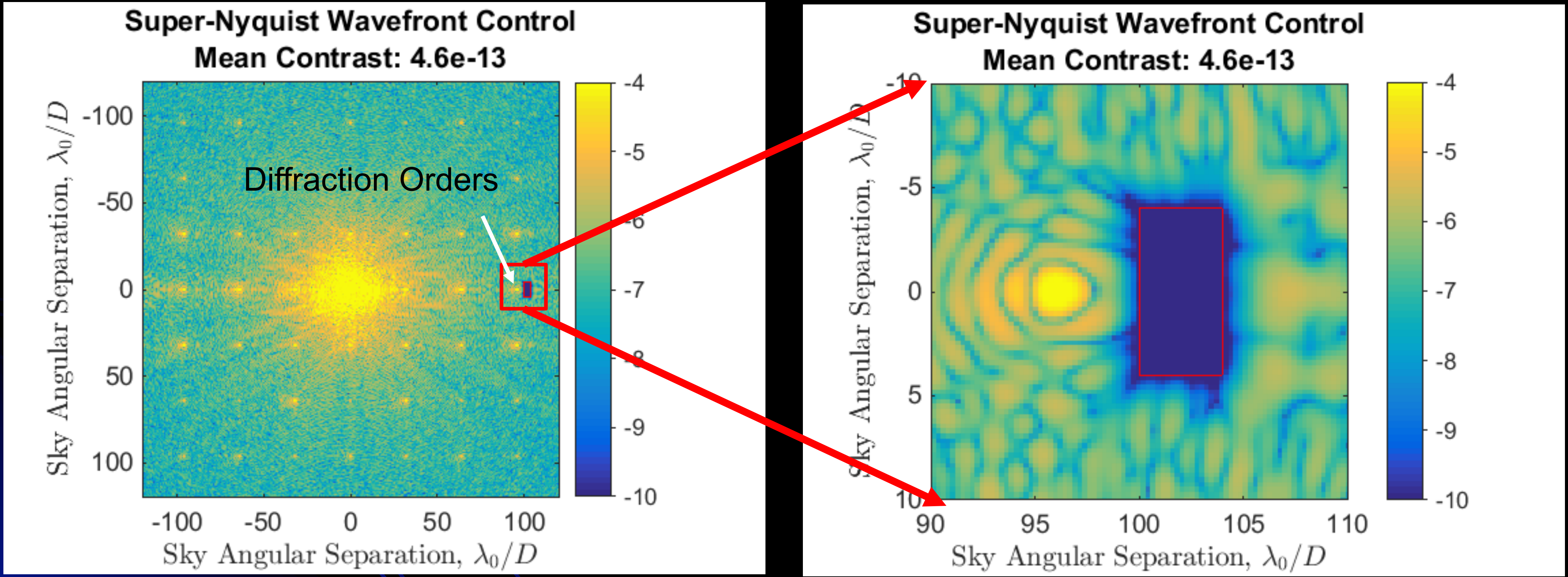




- Main idea: Diffraction orders or non-smooth influence functions enable the DM to modulate light beyond the Nyquist limit
  - Diffraction order effectively acts as a pseudo star, and almost any WF algorithm can be used to dig a dark hole (at a sub-Nyquist distance) around a diffraction order
  - Can also be understood in terms of aliasing
- If grating periodicity = DM actuator periodicity, then controllable diffraction order regions fully tile the entire focal plane (theoretically to infinity)

Super-Nyquist Wavefront Control

(single star, or multi-star w/starshade)



Super-Nyquist Wavefront Control
Mean Contrast: 4.6e-13

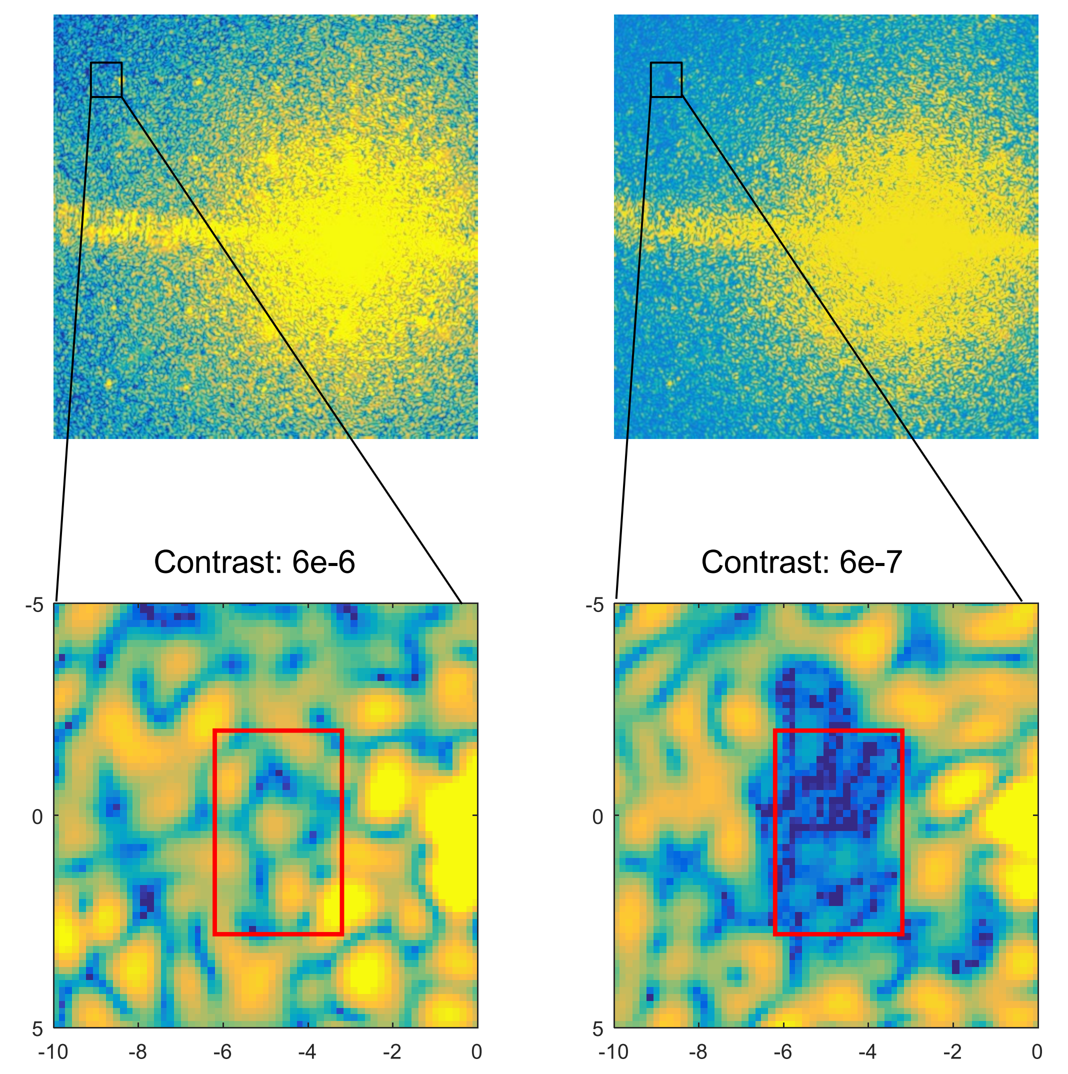
Diffraction Orders

Super-Nyquist Wavefront Control
Mean Contrast: 4.6e-13

Simulations by D. Sirbu
Also see Thomas et al. (2015), Belikov et al. (2016)

Super Nyquist WC Lab demo at 100 λ/D

(representative of aCen w / WFIRST-size telescope and starshade)



Belikov et al. 2017, SNWC operated by Pluzhnik

Details of this demonstration:

- In order to isolate pure WFC effects, coronagraph was not used
- For this initial demo, monochromatic light was used (655nm) rather than broadband
- DM: Boston Micromachines kilo (32x32)
- Performed at the Ames Coronagraph Experiment laboratory

Factor of 10 suppression demonstrated at 100 λ/D

SNWC using quilting or grating

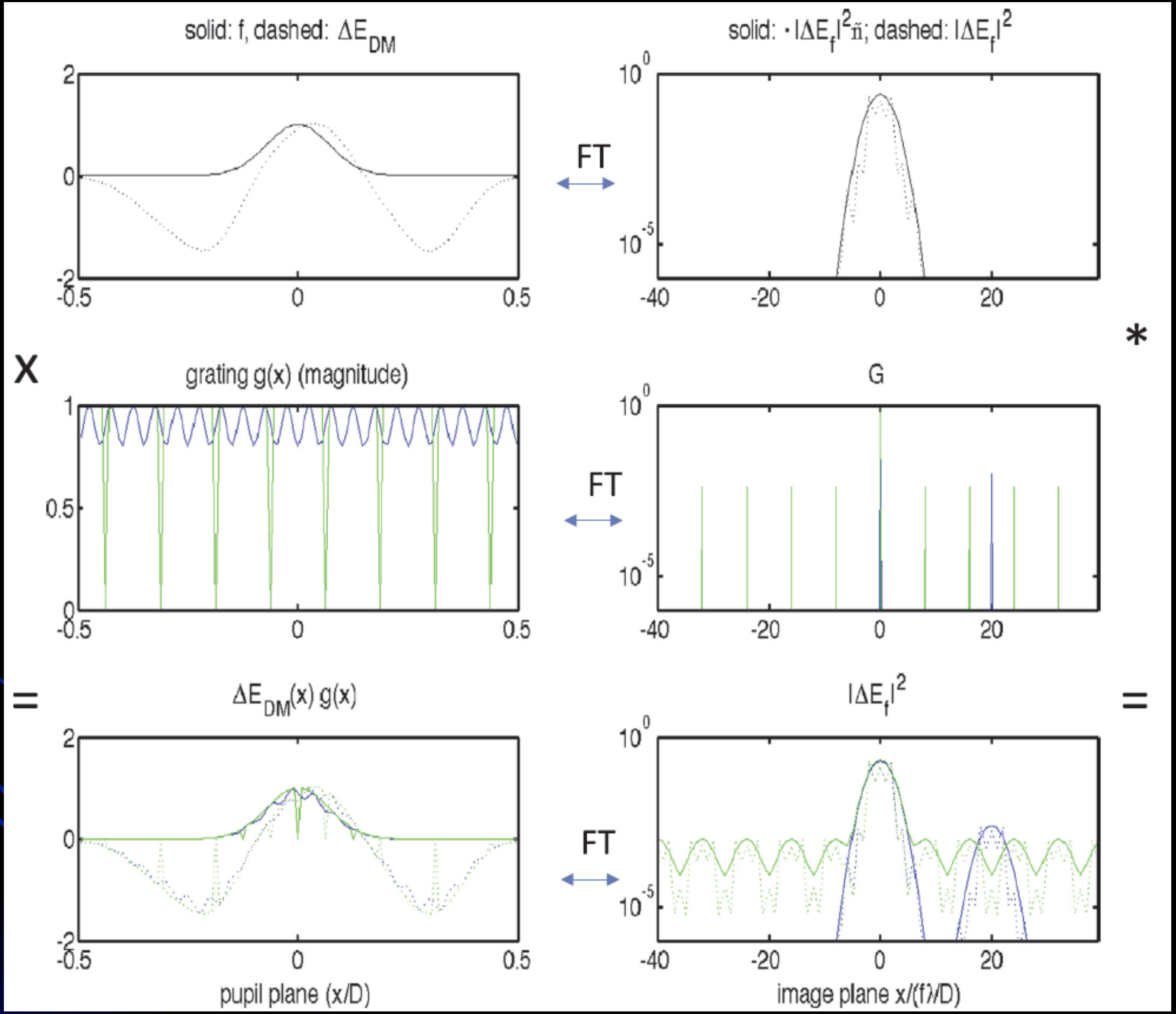
Pupil plane

Focal plane

Solid: influence function
Dashed: DM field perturbation

Grating (green) or
beamsplitter (blue)

DM field perturbation



Sub-Nyquist controllability curve

Super-Nyquist controllability curves (solid)

Thomas et al., ApJ, 2015

SNWC using special influence functions

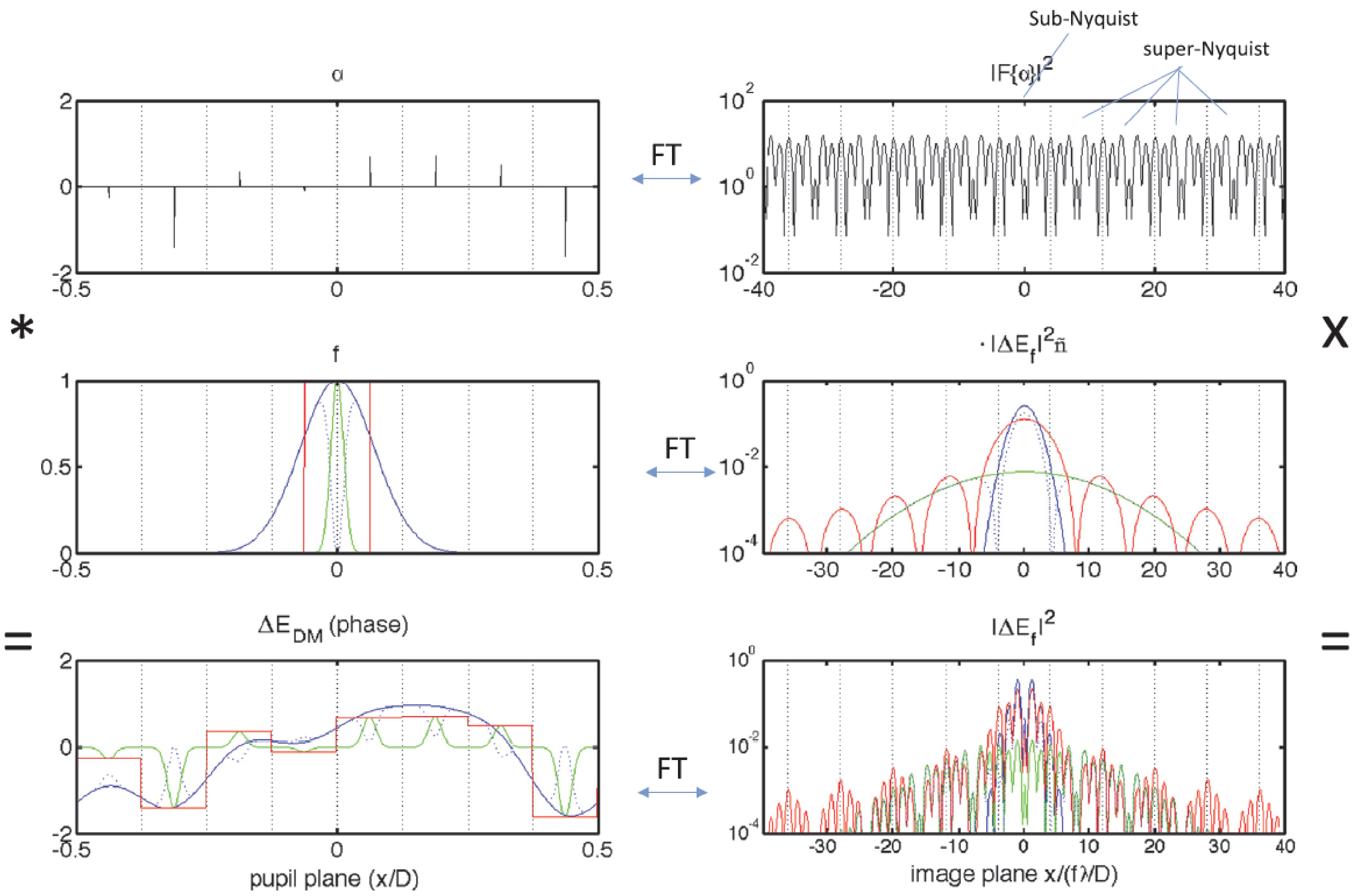
Pupil plane

Focal plane

DM actuator coefficients

Influence functions

DM field perturbation

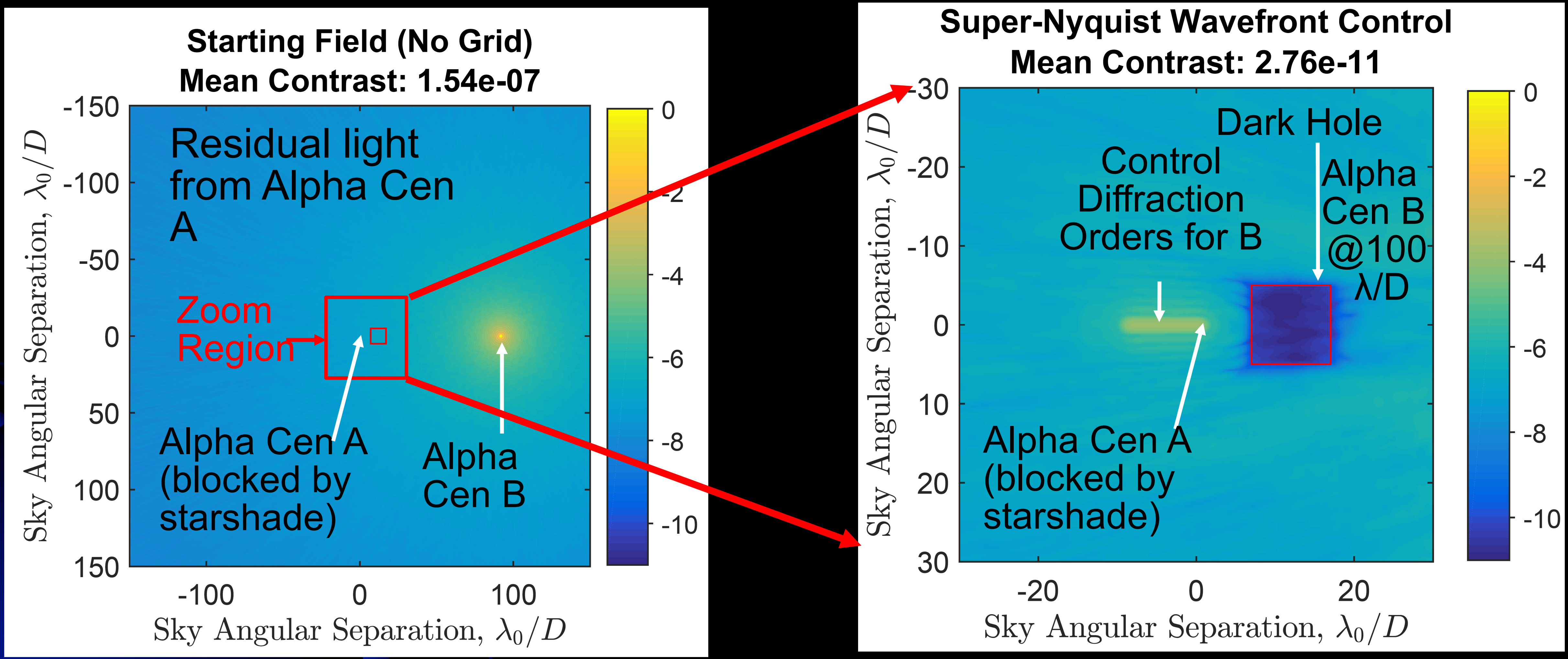


SNWC Controllability

Thomas et al., ApJ, 2015

10% Broadband SNWC simulation @ 100 λ/D

(similar to of aCen w/WFIRST)



Starting Field (No Grid)
Mean Contrast: 1.54e-07

Super-Nyquist Wavefront Control
Mean Contrast: 2.76e-11

Simulation by D. Sirbu

SCENARIO

WC SOLUTIONS

*Assuming DM = NxN actuators

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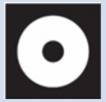
Coronagraph 	None (WC only)	**MSWC-0**	**MSWC-s**	**Existing coronagraphic mission concepts are already capable** of MSWC-0 with no hardware modifications. MSWC-s requires quilting on the DM or a mild grating in the pupil plane
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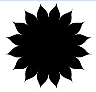
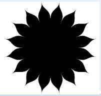
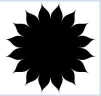
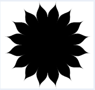
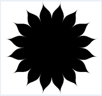
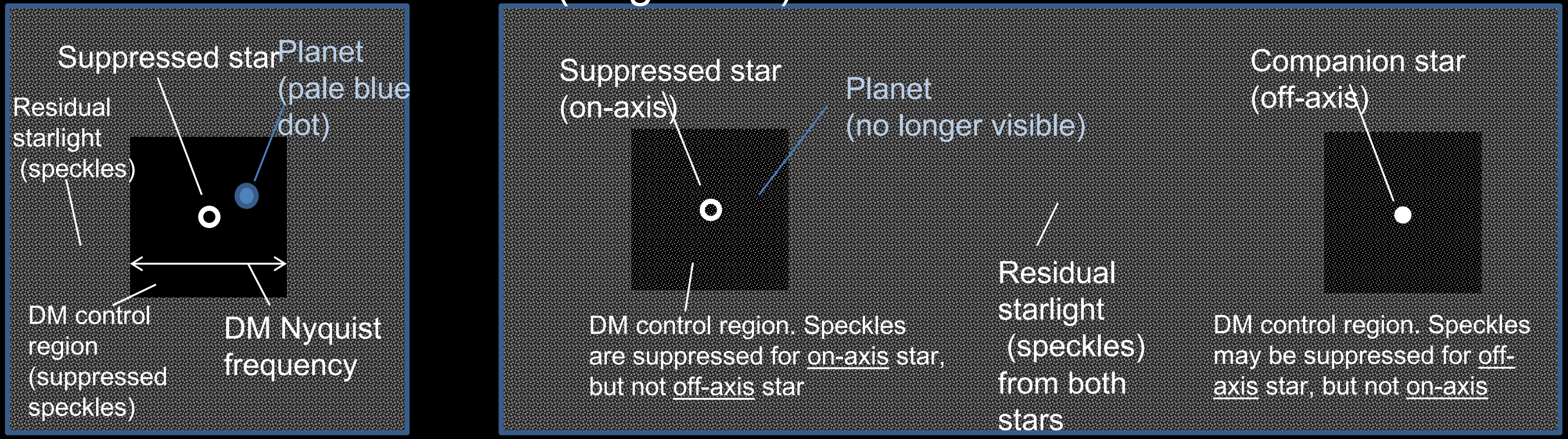
Coronagraph 	Starshade 	SSWC (i.e. standard WC)	SSWC (i.e. standard WC)	Adding a starshade effectively **reduces binaries to single-star** suppression problem, at a **cost of adding a starshade**
Starshade 	None (WC only)	SSWC (i.e. standard WC)	**SNWC**	**Adding a deformable mirror** (without a coronagraph) to a starshade mission theoretically **enables double-star suppression**
Starshade 	Coronagraph 	SSWC (i.e. standard WC)	**SNWC**	**The off-axis coronagraph is not necessary** for a well-baffled telescope, but may relax the stroke requirement on the DM for close stars
Starshade 	2nd Starshade 	No WC required	No WC required	Adding a starshade for the off-axis star effectively **reduces binaries to single-star** suppression problem, but at a **cost of adding a second starshade**

SSWC=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, MSWC-0 = Multi-Star WC (0th order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)

MSWC with super-Nyquist separations (MSWC-s)

Conventional (single star) wavefront control



Suppressed star

Planet
(pale blue
dot)

Residual
starlight
(speckles)

DM control
region
(suppressed
speckles)

DM Nyquist
frequency

Suppressed star
(on-axis)

Planet
(no longer visible)

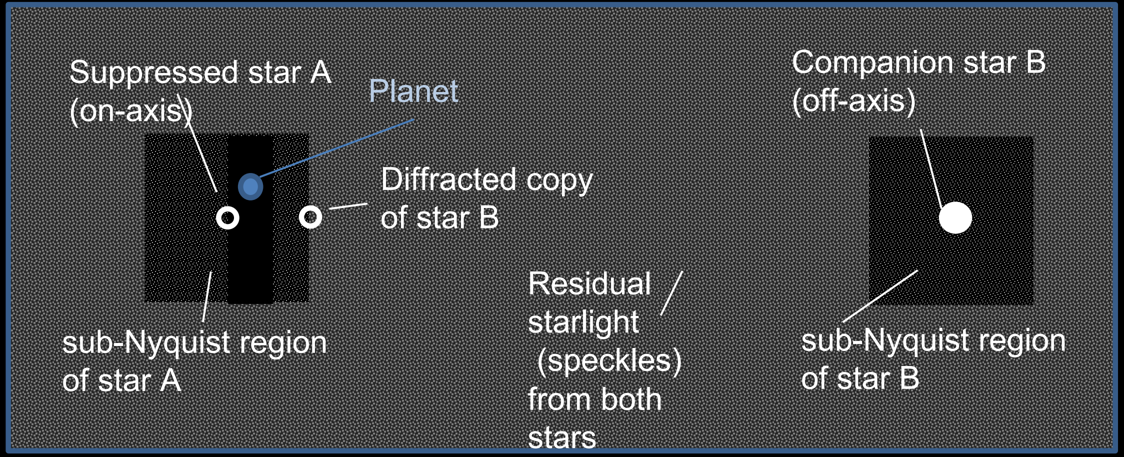
Companion star
(off-axis)

DM control region. Speckles
are suppressed for <u>on-axis</u> star,
but not <u>off-axis</u> star

Residual
starlight
(speckles)
from both
stars

DM control region. Speckles
may be suppressed for <u>off-axis</u> star, but not <u>on-axis</u>

MSWC-s



Suppressed star A
(on-axis)

Planet

Companion star B
(off-axis)

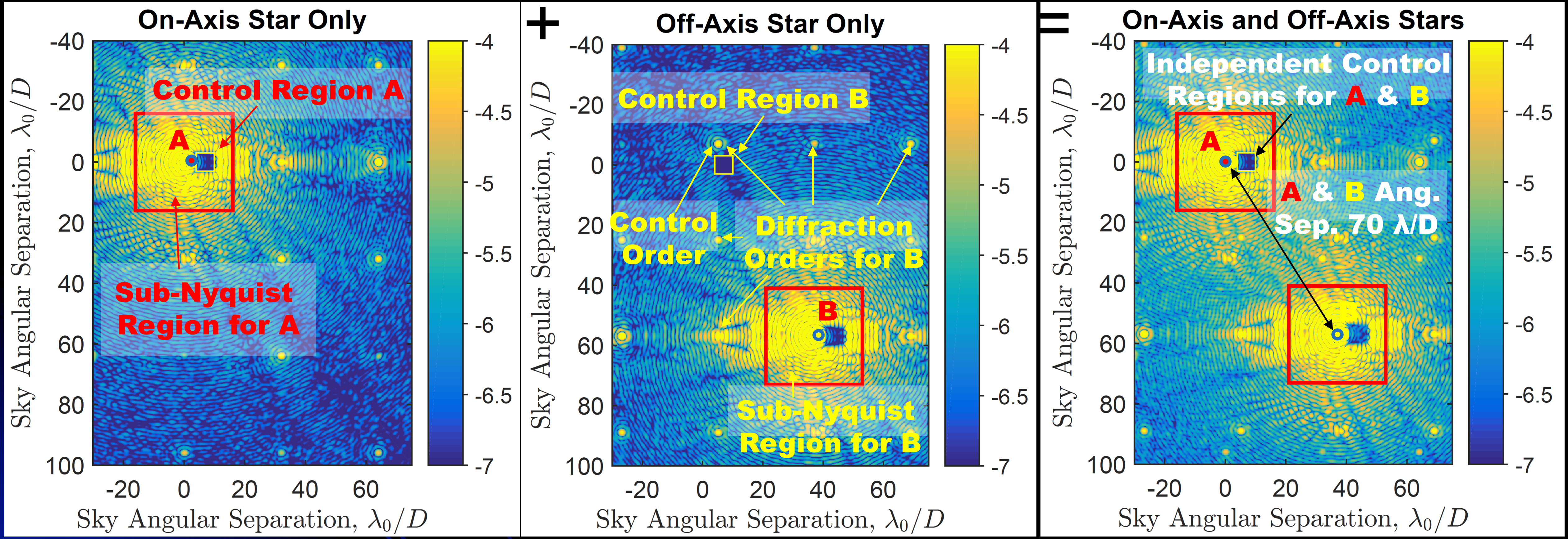
Diffracted copy
of star B

sub-Nyquist region
of star A

Residual
starlight
(speckles)
from both
stars

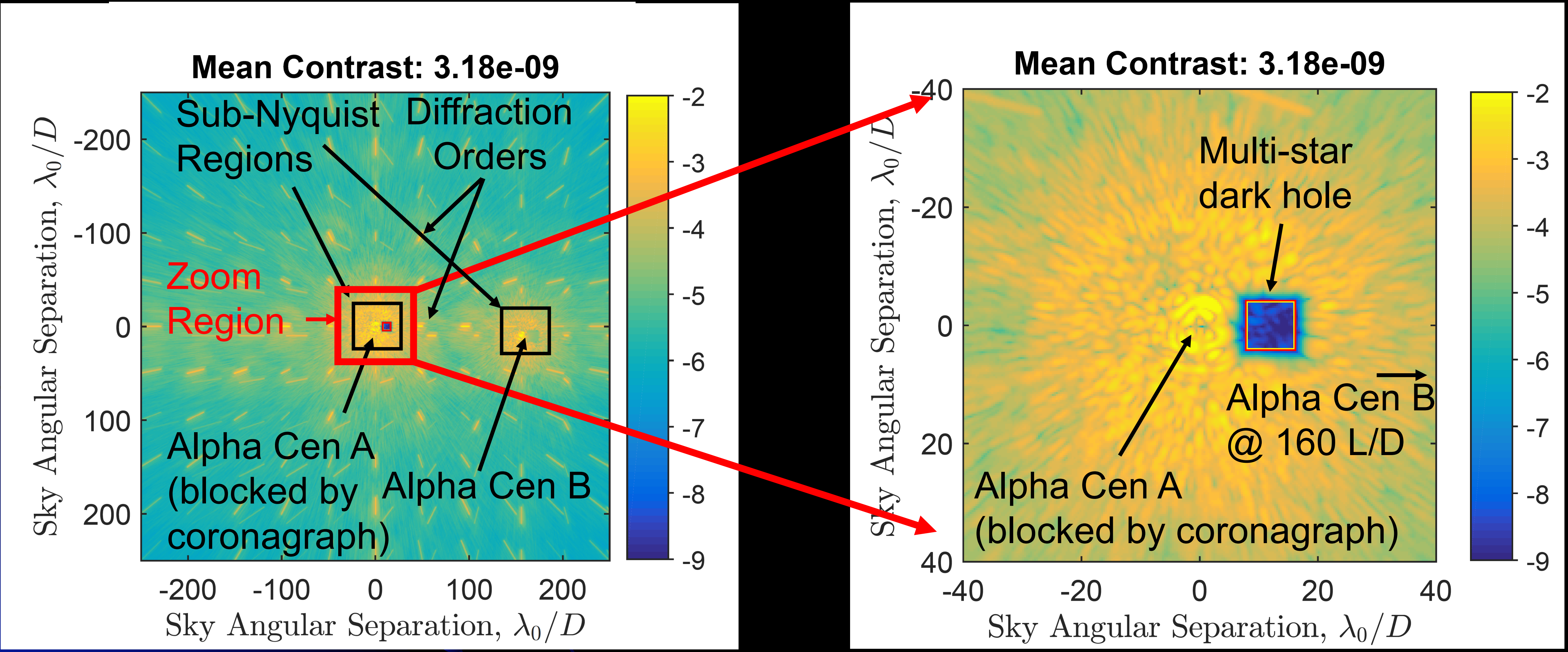
sub-Nyquist region
of star B

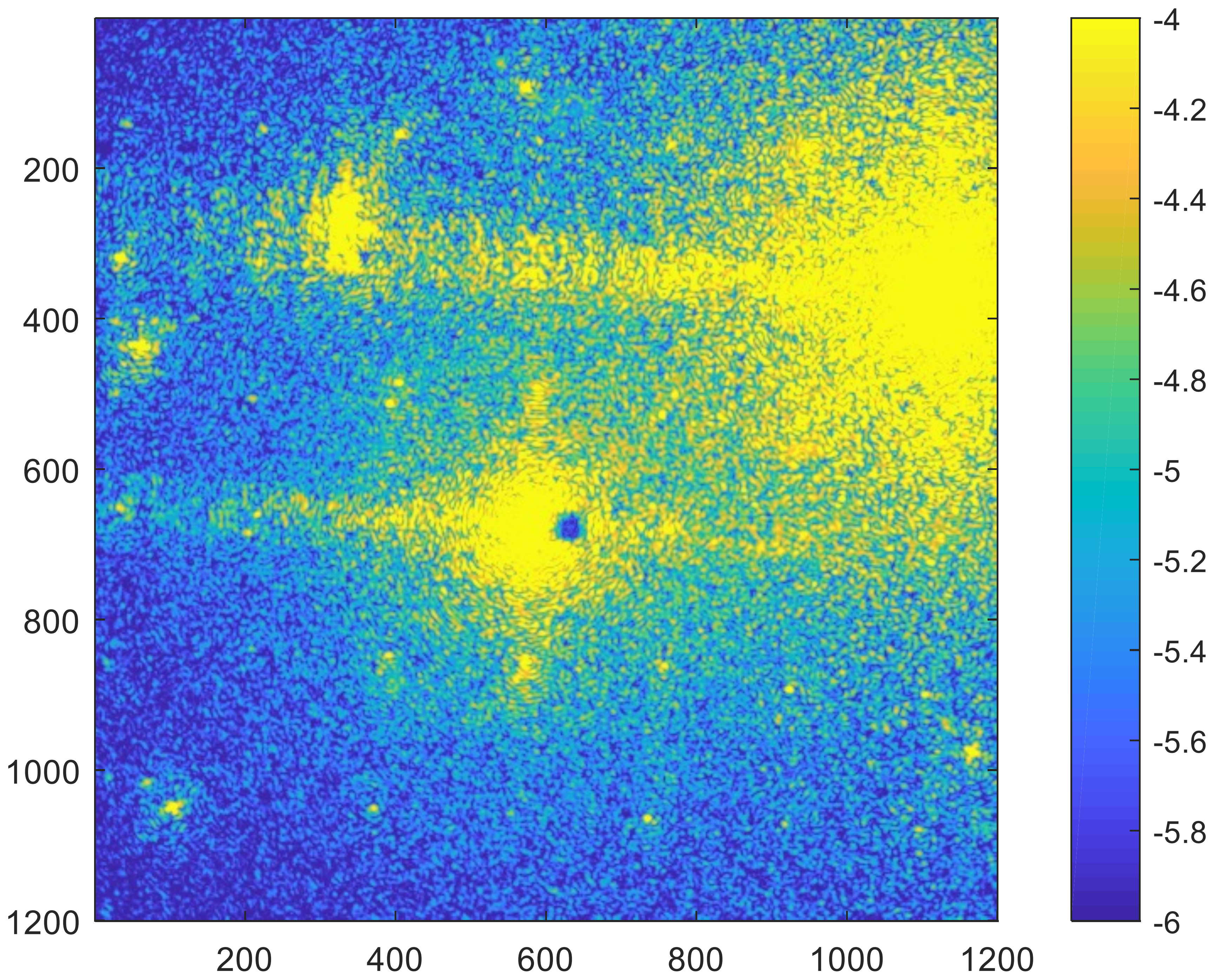
MSWC with Super-Nyquist separations (MSWC-s) simultion

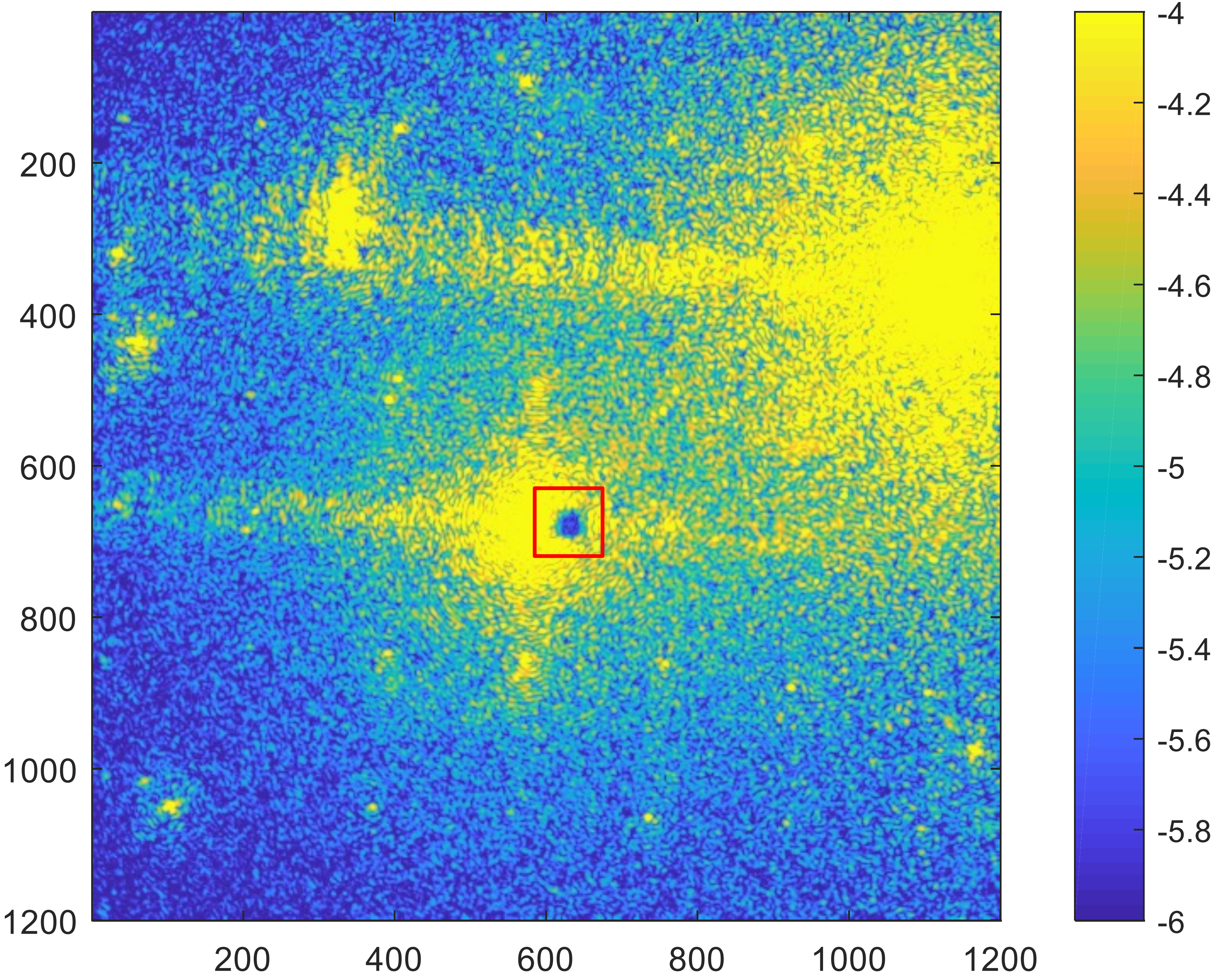


Simulations by D. Sirbu

MSWC-s in 10% broadband light (simulation)




200
400
600
800
1000
1200
200
400
600
800
1000
1200
-4
-4.2
-4.4
-4.6
-4.8
-5
-5.2
-5.4
-5.6
-5.8
-6


200
400
600
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1200
200
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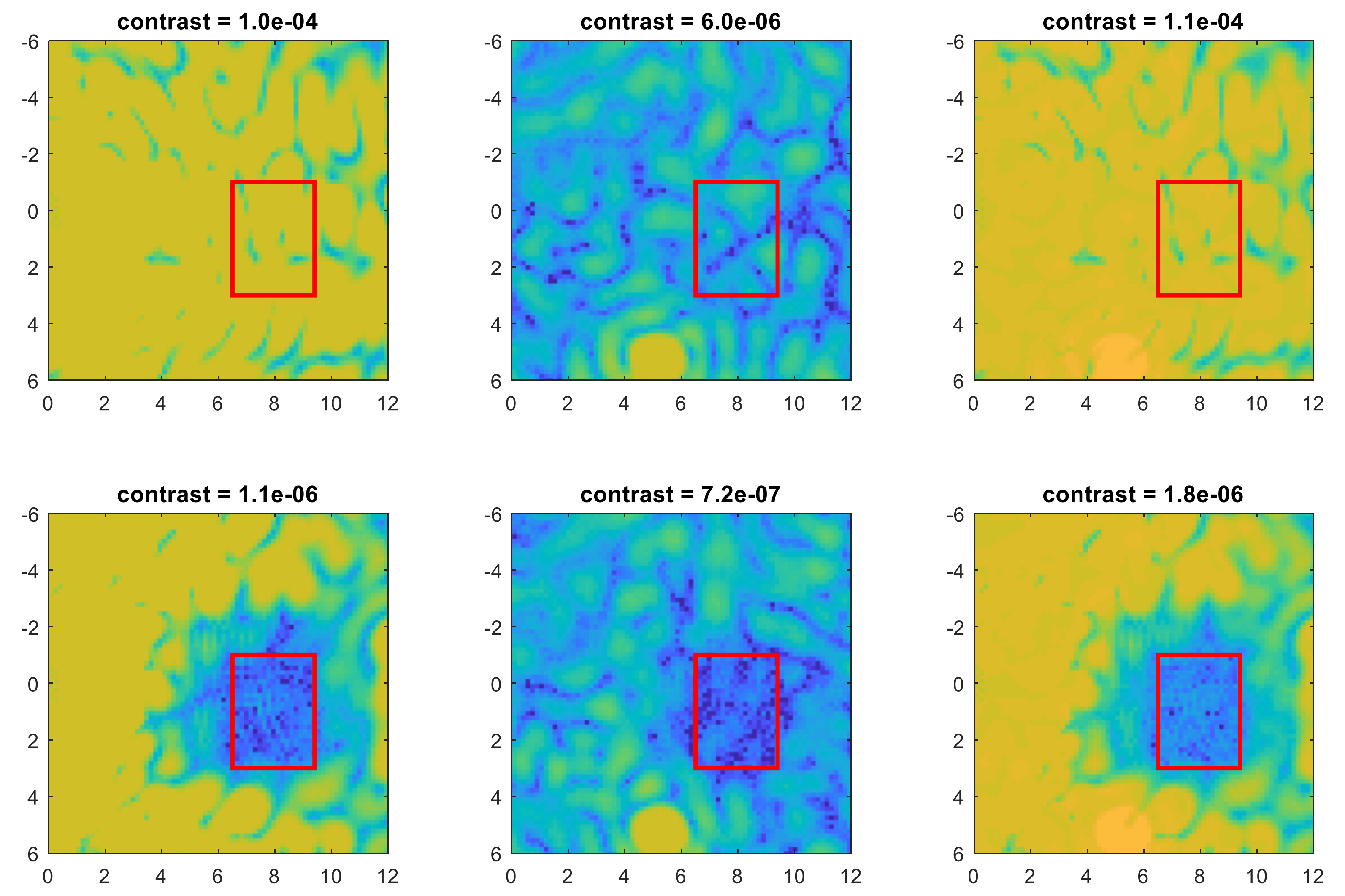
600
800
1000
1200
-4
-4.2
-4.4
-4.6
-4.8
-5
-5.2
-5.4
-5.6
-5.8
-6

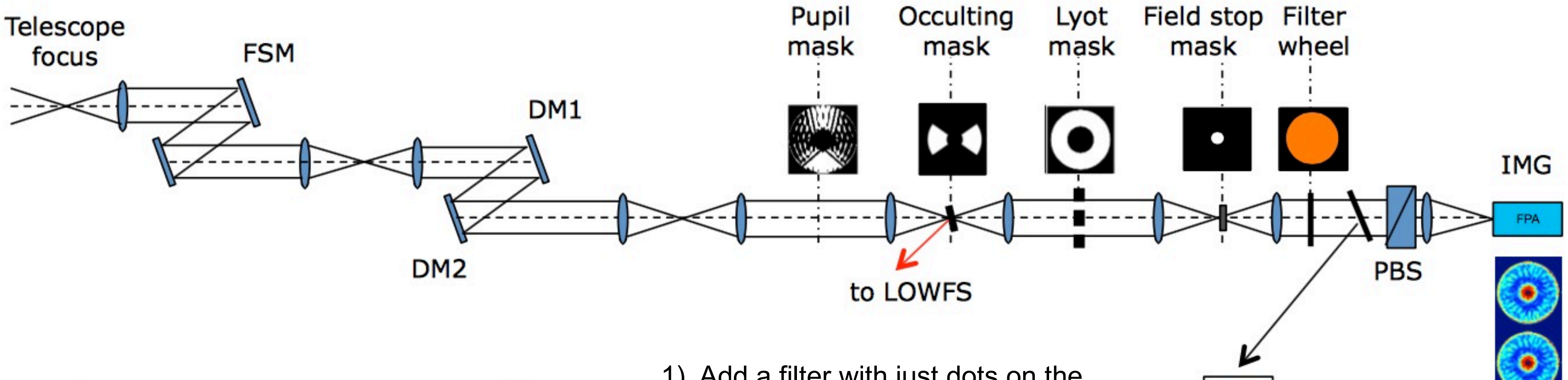
MSWC-s lab demonstration @ ~100 λ/D

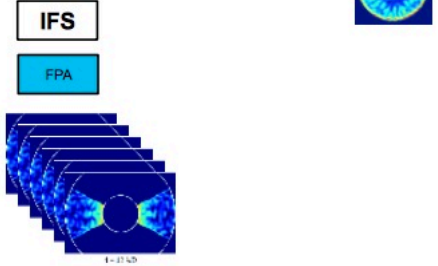


Star separation
Representative of
aCen w/WFIRST

Belikov et al., 2017 (MSWC-s operation by Pluzhnik)

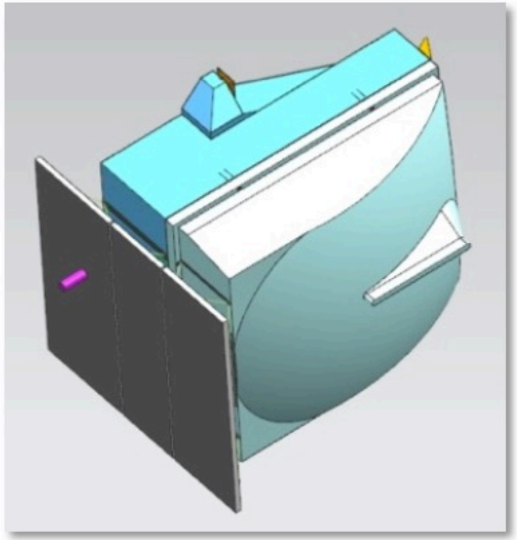
How to create “proxy stars” on WFIRST





1) Add a filter with just dots on the surface in a open position on the pupil mask wheel ,

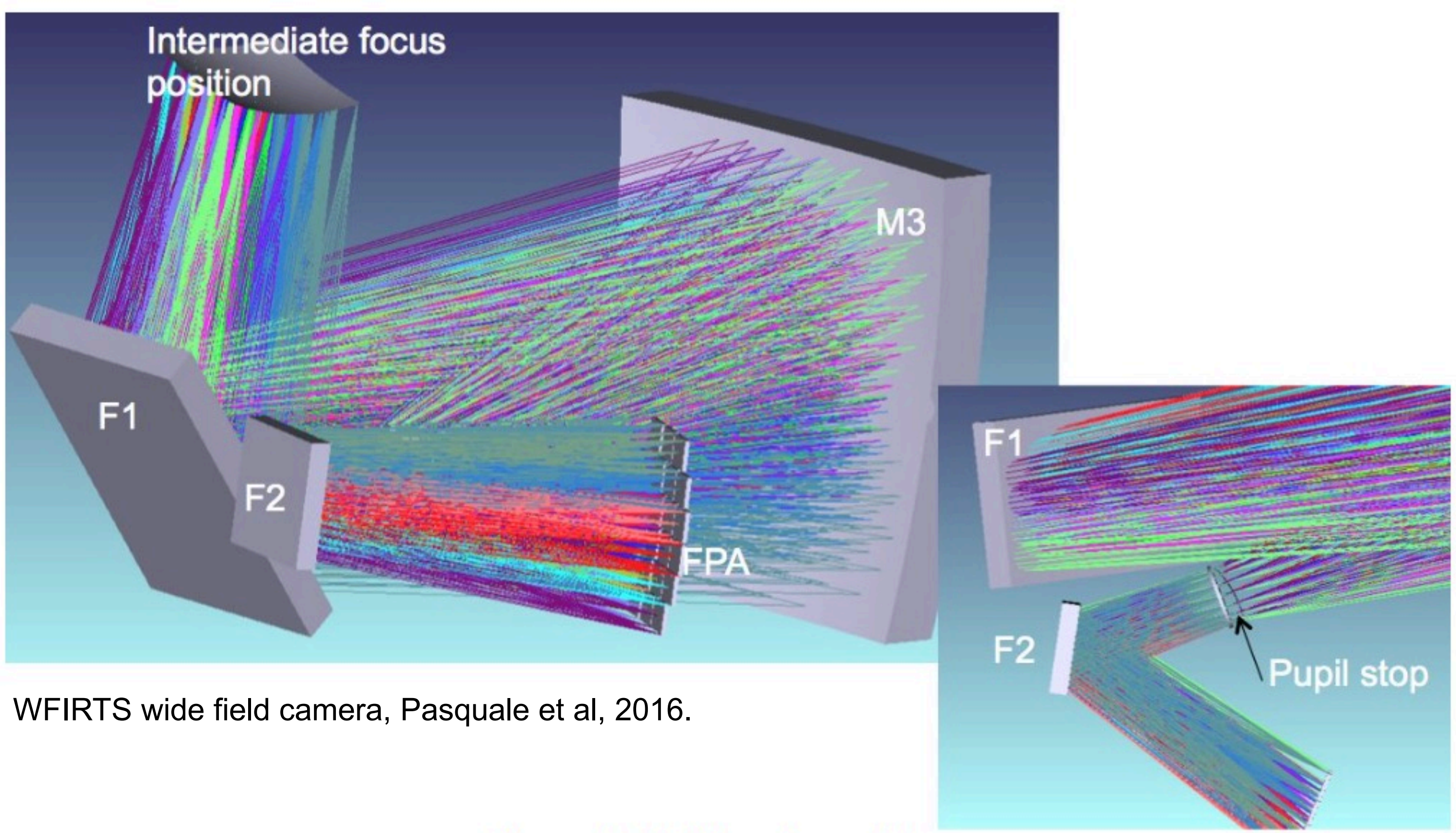
Then, only the HCL can be used



3

WFIRST CORONAGRAPH, Kasdin et al, AAS 2015.

Side note for WFIRST wide field camera



Add a diffractive pupil filter here

WFIRTS wide field camera, Pasquale et al, 2016.

Figure 7. WFI Ray Trace Views

Adding a DP filter at the pupil stop can calibrate:
- Any distortions induced by the last mirror
- Detector motions
- Individual pixels motions were the spikes are located.

Also, for exoplanet stellar astrometric measurements, it allows to put the target star in chip gap to allow longer integration and achieve a similar brightness between the spikes and the background stars,

Eduardo Bendek

Future work

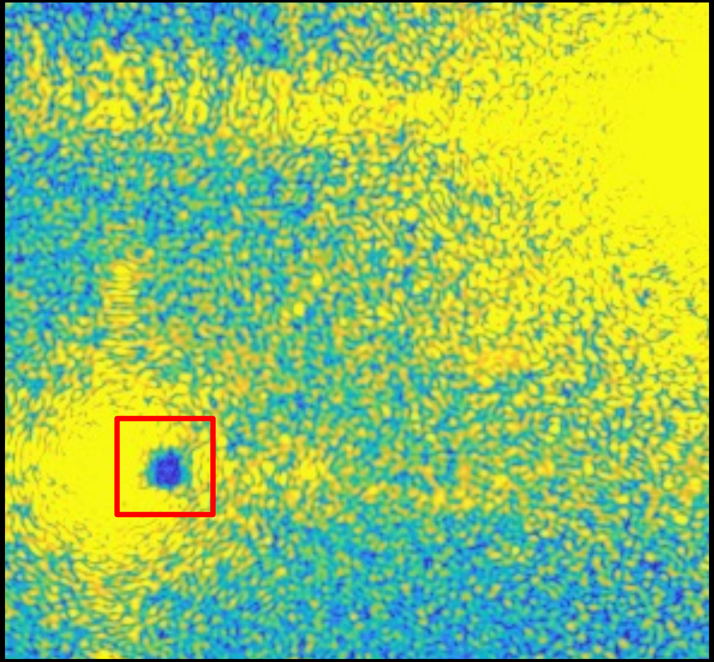
- Recently funded TDEM (CY18 – 19): TRL 3 -> 4
  - 1. Simulations of MSWC with mission instrument models and real binary star geometries
  - 2. Testing of MSWC on SCExAO (Subaru Telescope)
  - 3. Testing of MSWC at ACE testbed with apertures representative of missions, as well as with a coronagraph
- HCIT vacuum testing? (TRL4 -> 5)
  - Potential collaborations with existing tests at HCIT
  - Stand-alone proposals for FY19 or late FY18.

Conclusions

- Multi-star high contrast imaging opens up the majority of (non-M-dwarf) star systems
    - Alpha Centauri in particular
        - If aCen has a rocky planet in HZ, it may be possible to directly image it in 5-10 years (ACESat or WFIRST)

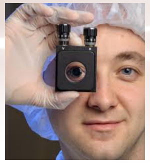
- General binary star suppression requires binary star wavefront control algorithms
    - Solution: MSWC (-0 and -s versions)
    - 3e-11 in 10% achieved in simulation

- TRL ~3 lab demonstrations
    - Super-Nyquist dark zones demonstrated at 16-300 λ/D with a 32x32 DM
    - MSWC for (effectively) 2 light sources
        - both sub- and super-Nyquist versions



A Method to Enable High Contrast Imaging in Multi-Star Systems

PI: Ruslan Belikov / NASA ARC

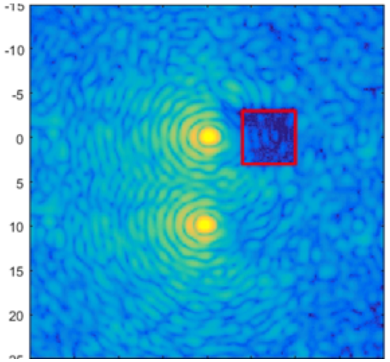


Description and Objectives:

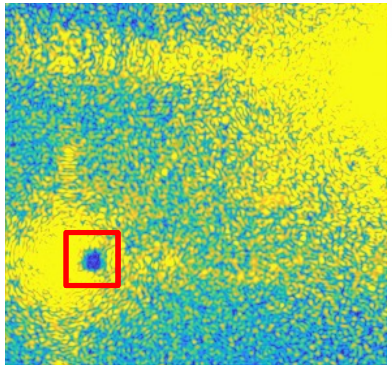
- Develop technology to directly image exoplanets in multi-star systems, the most common type of (Sun-like) star system

Key Challenge/Innovation:

- Challenges:
  - Starlight from both stars needs to be independently suppressed
  - Star separation is usually beyond the outer working angle of the deformable mirror
- Innovations:
  - Using different deformable mirror (DM) modes for different stars
  - Using quilting pattern on DM or a grating to overcome its outer working angle limitation



Milestone 2 met:
Starlight suppression lab demo for sub-Nyquist binary system



Milestone 3 (and 1) met:
Starlight suppression lab demo for super-Nyquist binary star system

Approach:

- Develop three algorithms in simulation and then perform a lab demonstration:
  - Super-Nyquist Wavefront Control (SNWC) to overcome DM outer working angle limitation
  - 0-th order Multi-Star Wavefront Control (MSWC-0) to suppress binary stars at sub-Nyquist separations
  - Combination of MSWC-0 and SNWC (MSWC-s) to suppress binary stars at super-Nyquist separations

Key Collaborators:

- NASA Ames Research Center: Ruslan Belikov, Eduardo Bendek, Eugene Pluzhnik, Dan Sirbu, Chris Henze, Sandrine Thomas
- University of Arizona: Olivier Guyon

Development Period:

- 4/2015 – 3/2017

Accomplishments and Next Milestones:

- Methods proved in computer simulations for 10% broadband light:
  - SNWC: **3e-11 contrast** at 100 l/D
  - MSWC-0 (with coronagraph): **8.3e-9 contrast** for αCen AB with a 35cm telescope
  - MSWC-s (with coronagraph): **2.3e-9 contrast** for αCen AB with HabEx – size telescope
- All milestones so far met: SNWC and MSWC lab demos
- Next: follow-on SAT / TDEM effort to raise from TRL3 to 4

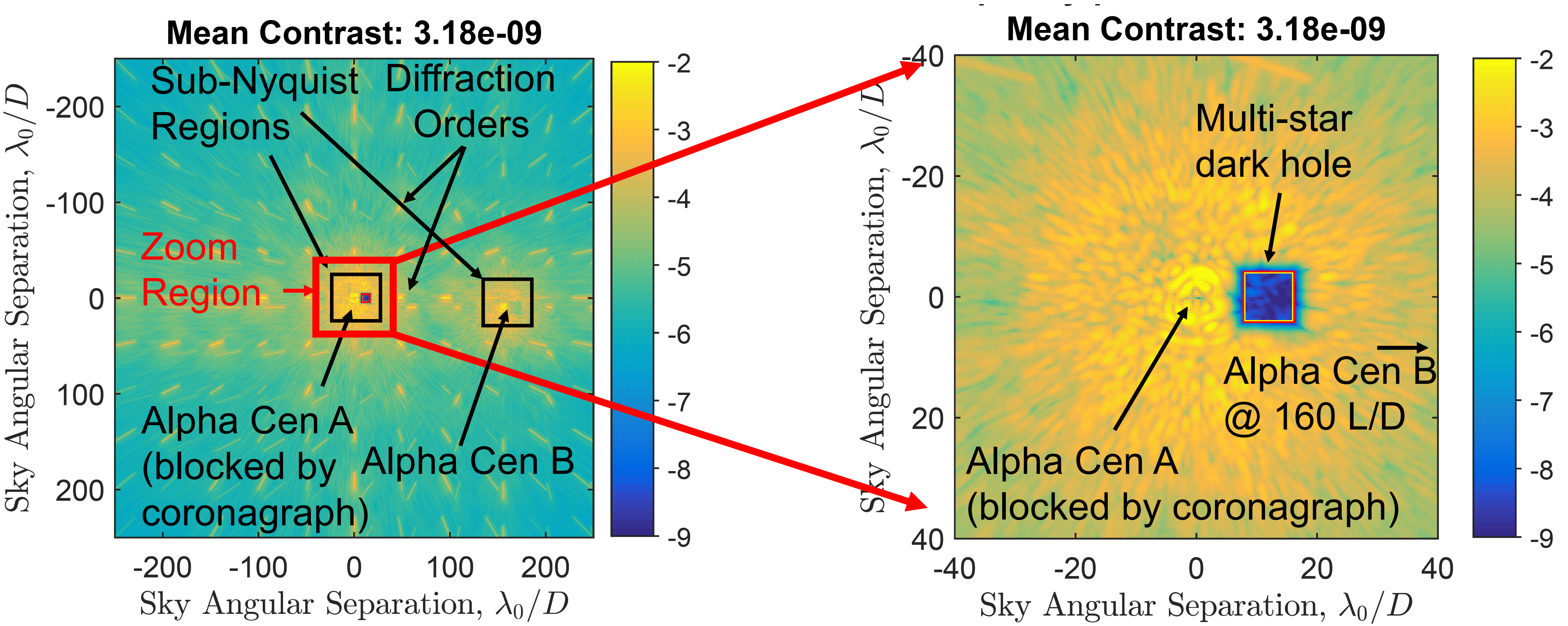
Publications:

- **Sirbu, D., Thomas, S., Belikov, R., Bendek, E., *ApJ* (2017)**
- Belikov, R., Pluzhnik, E., Bendek, E., Sirbu, D., *SPIE* (2017)
- Sirbu, D., Belikov, R., Bendek., E., Holte, E., et al., *SPIE* (2017)
- Belikov. R., Bendek, E., Pluzhnik., E., Sirbu, D., et al., *SPIE (2016)*.
- Belikov, R., Bendek, E., Thomas, S., Males, J., Lozi, J., *SPIE* (2015)
- **Thomas, S., Belikov, R., Bendek, E., *ApJ* (2015).**
- Thomas, S., J., Belikov, R., Bendek, E.A., *SPIE* (2015).

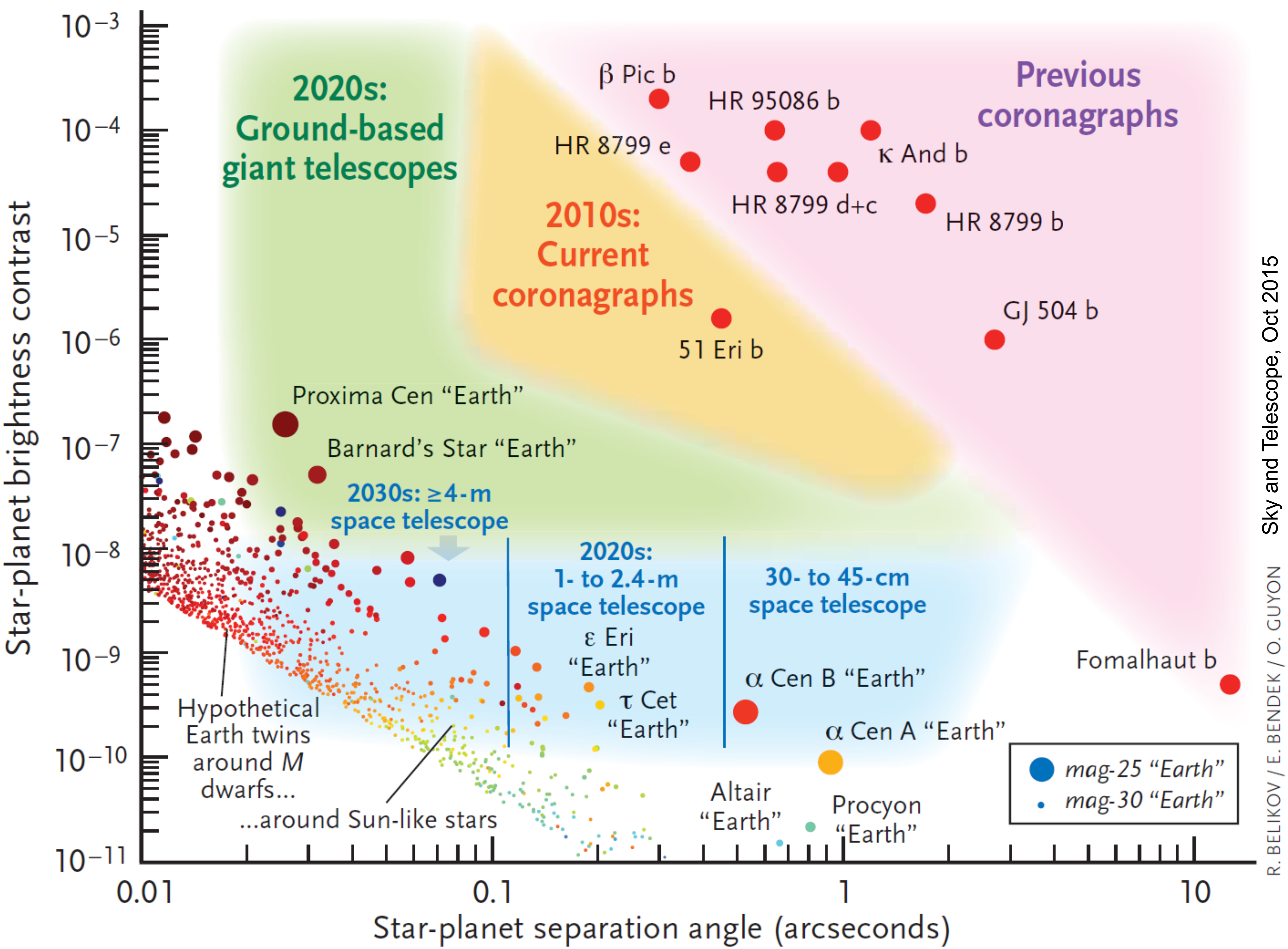
*TRLin = **1*** *TRLcurrent = 3* *TRLtarget = 3*

BACKUP SLIDES

MSWC-s in 10% broadband



→48x48 DM's nominal Nyquist Limit is 24 λ/D

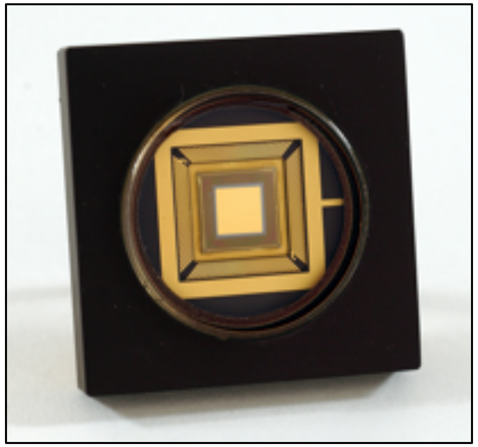


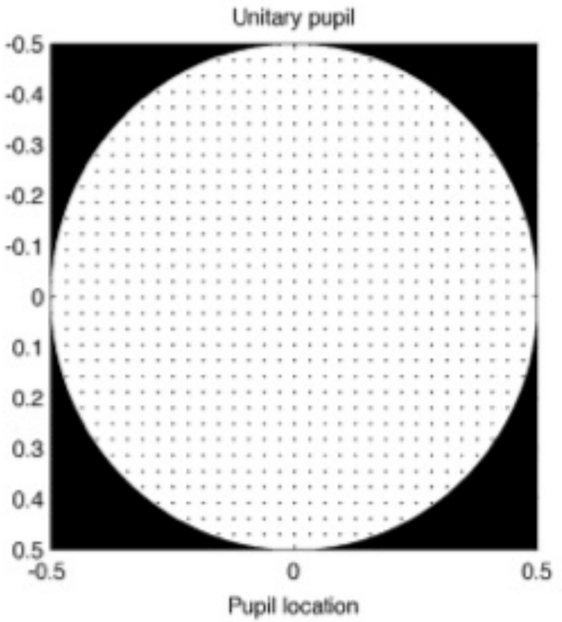
Sky and Telescope, Oct 2015

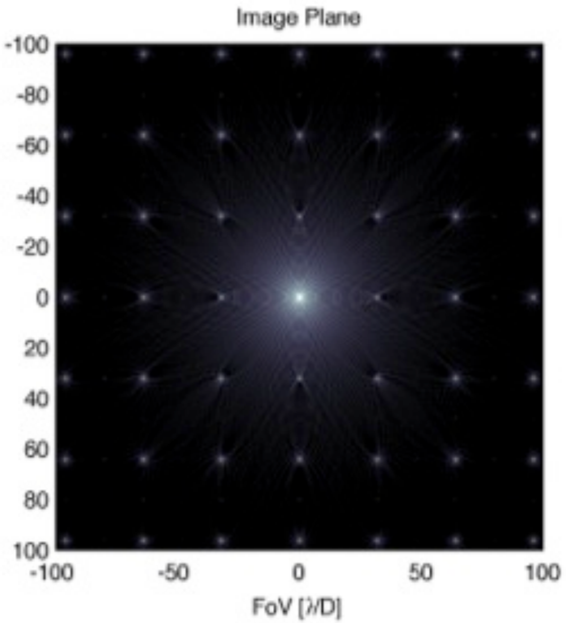
R. BELIKOV / E. BENDEK / O. GUYON

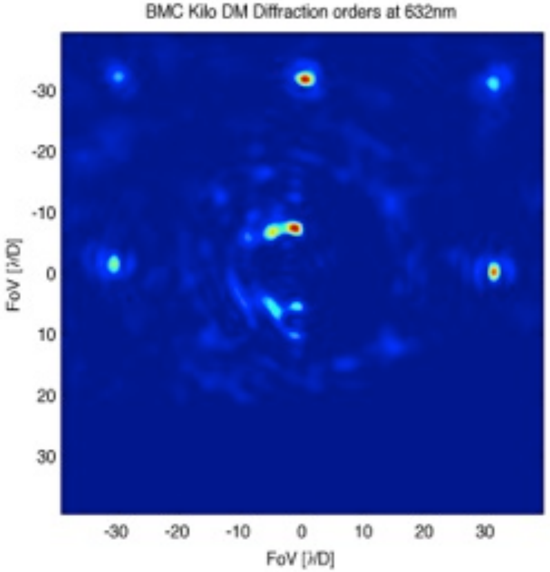
How to create PSF replica?

- We can use DM manufacturing dots
- Use a Diffractive Pupil to generate dots at an arbitrary distance.

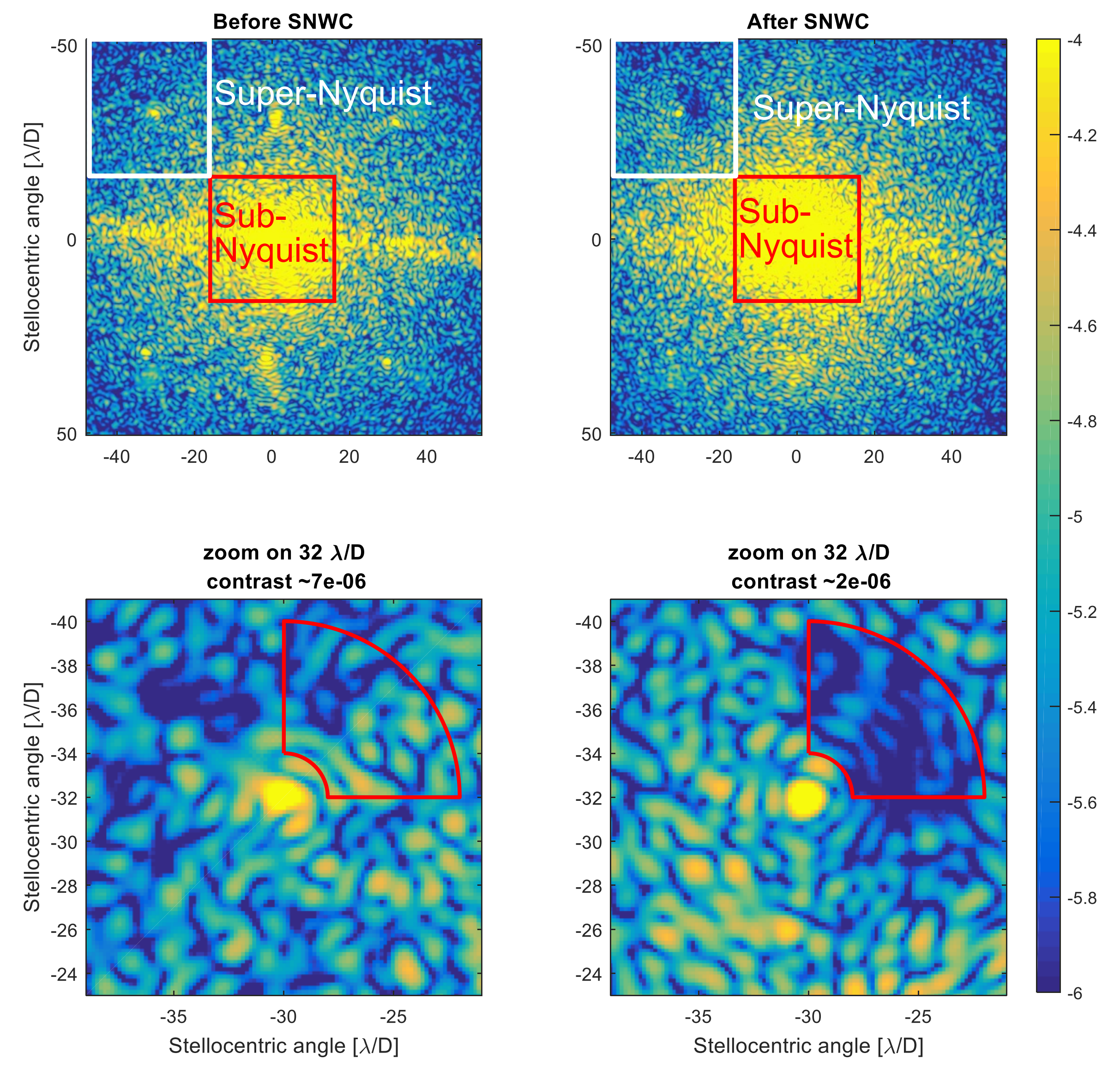








Super-Nyquist Wavefront Control Preliminary Lab Demo

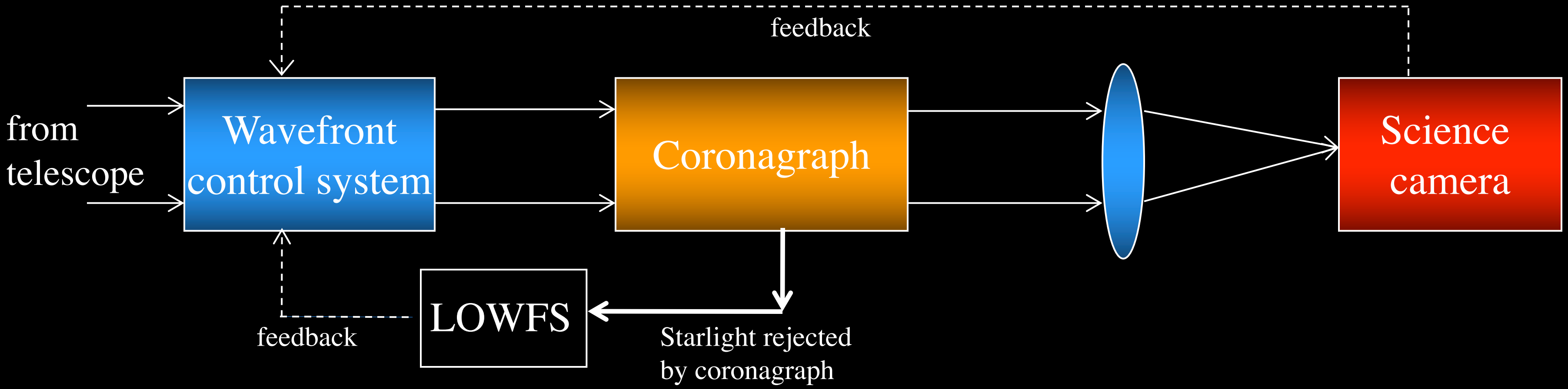


Details of this demonstration:

- In order to isolate pure WFC effects, coronagraph was not used
- For this initial demo, monochromatic light was used (655nm) rather than broadband
- DM: Boston Micromachines kilo (32x32)
- Performed at the Ames Coronagraph Experiment laboratory

SNWC Theory+simulations: Thomas, Belikov, Bendek 2015

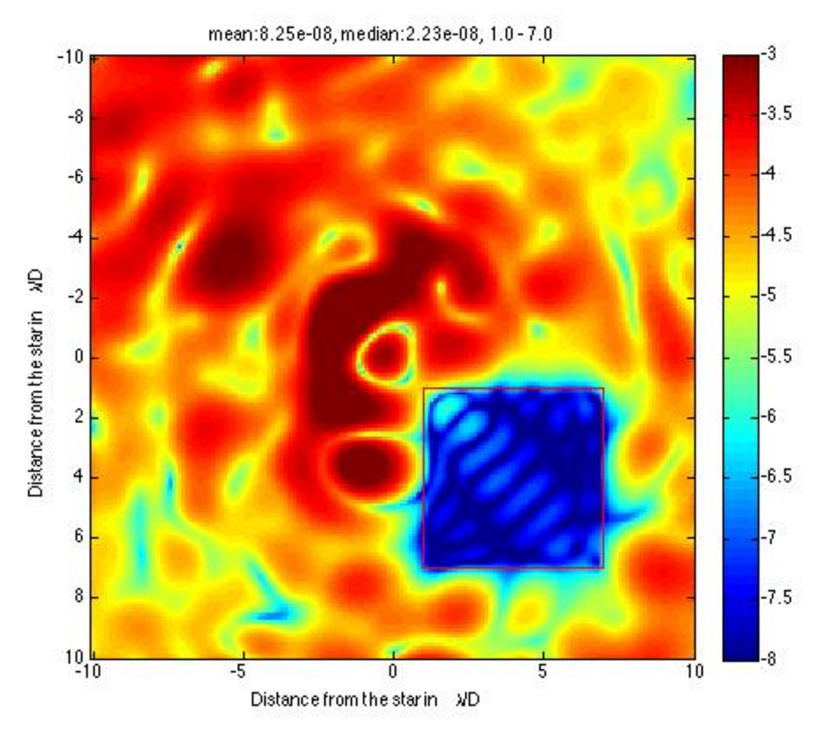
Fundamental challenges in high contrast imaging



- Challenge #1: Diffraction (known a priori)
  - Solution: Coronagraph / Starshade
  - Coronagraph is not necessary for second star
- Challenge #2: Aberrations (random error)
  - Wavefront Control (WFC)
  - Multi-star wavefront control is necessary

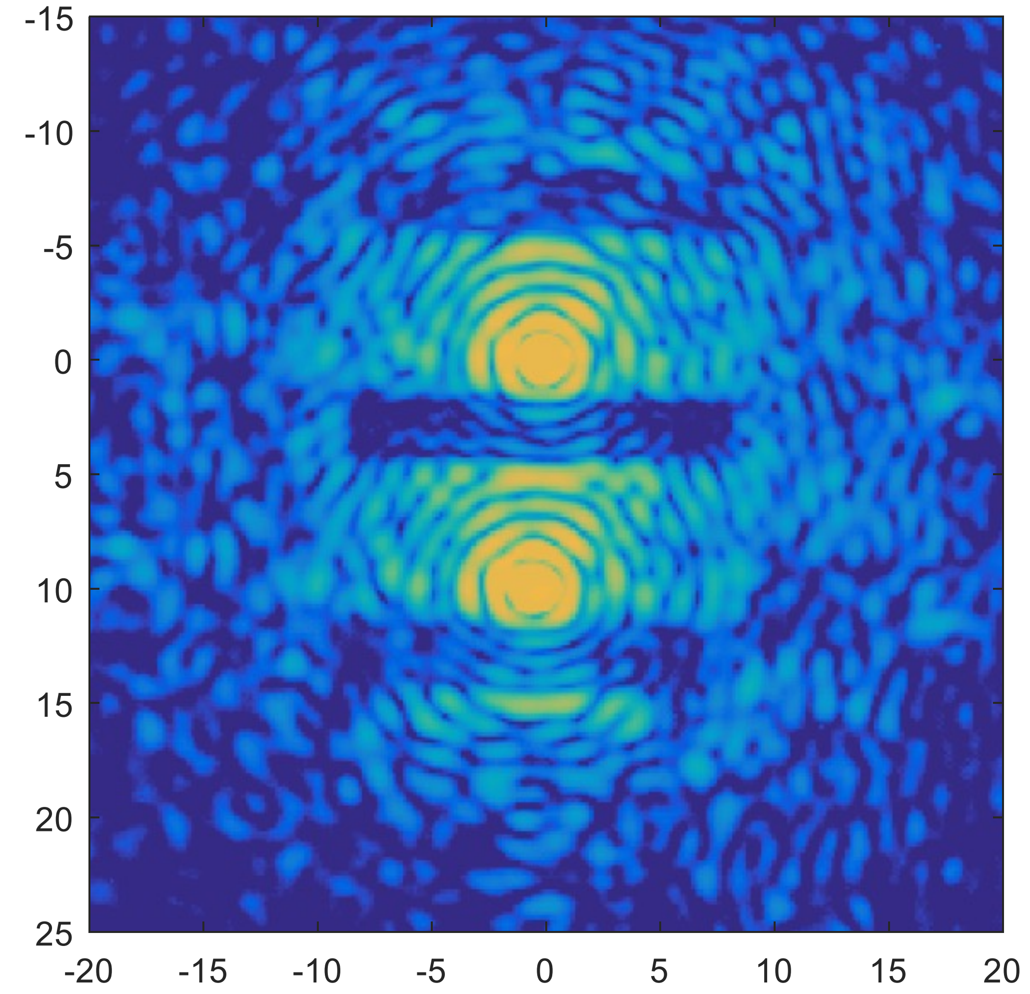
MSSNWC Simulation with a coronagraph

- **monochromatic light**
- Star separations: 25 λ/d
- Contrast achieved: **2x10^{-8}** with a 6x6 λ/d region.
- With a 4x4 λ/d region contrast is < 10^{-8}

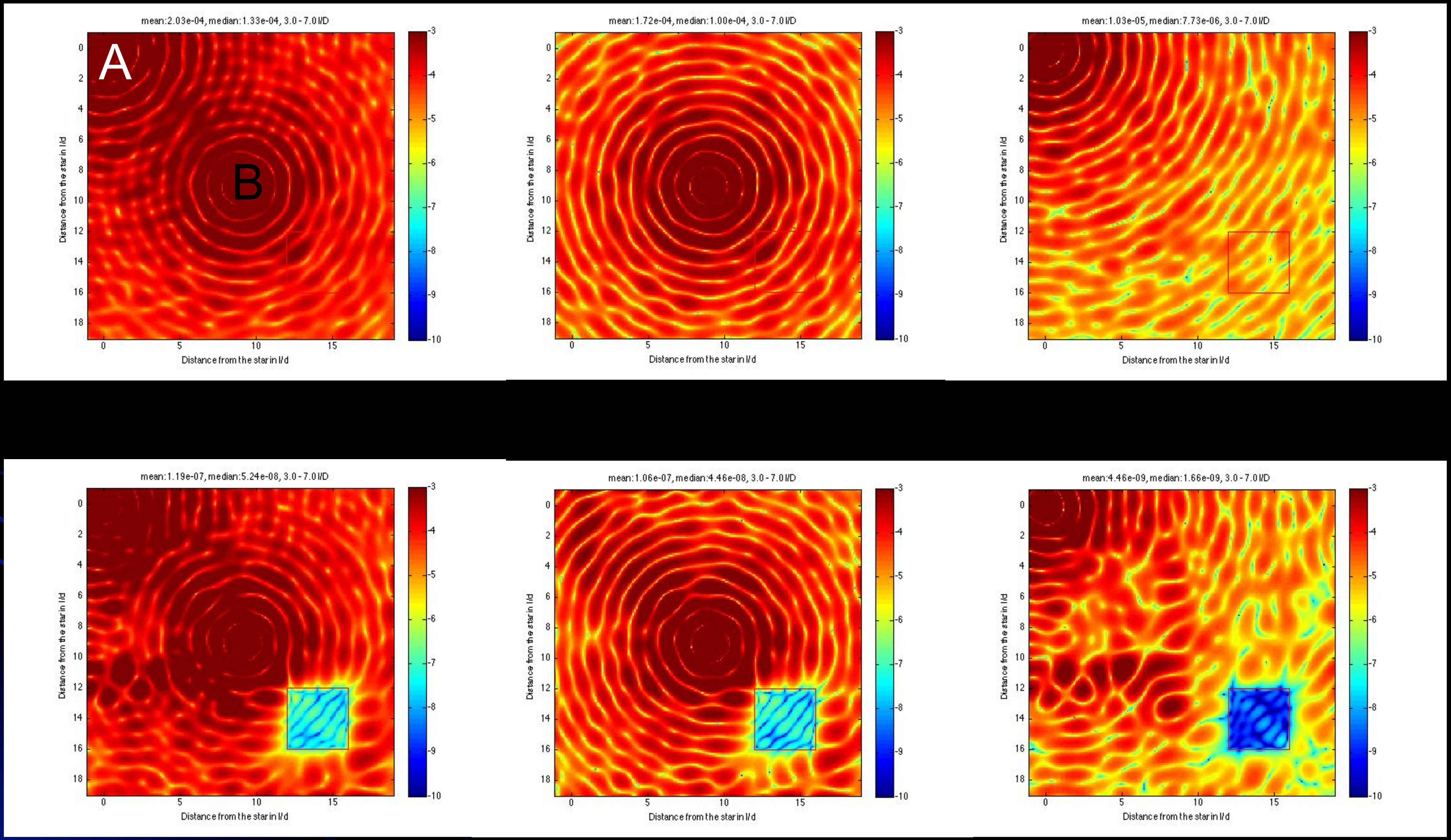


Simulation by Sandrine Thomas

Example of a different dark zone geometry (lab image)

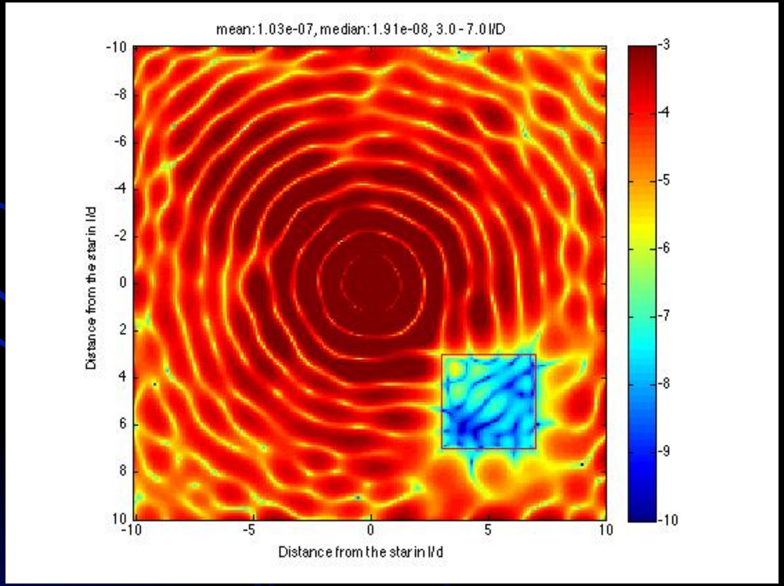


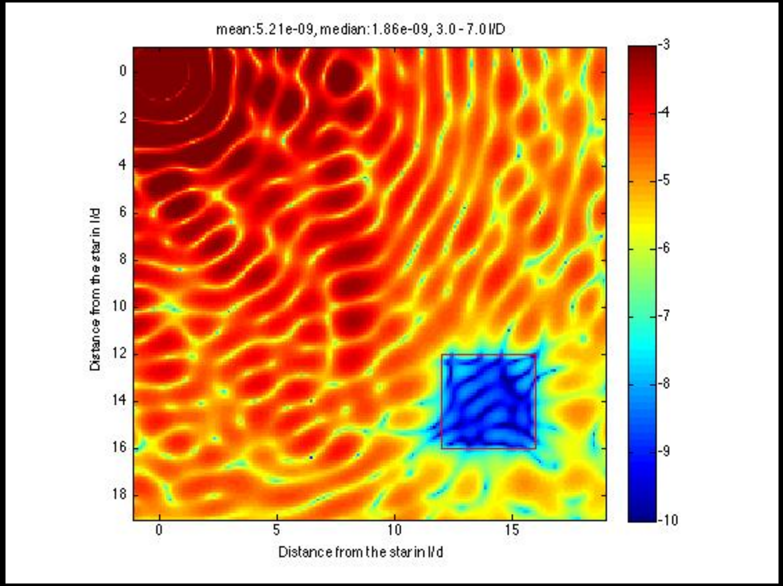
Multi-star wavefront correction
Proof of principle simulation



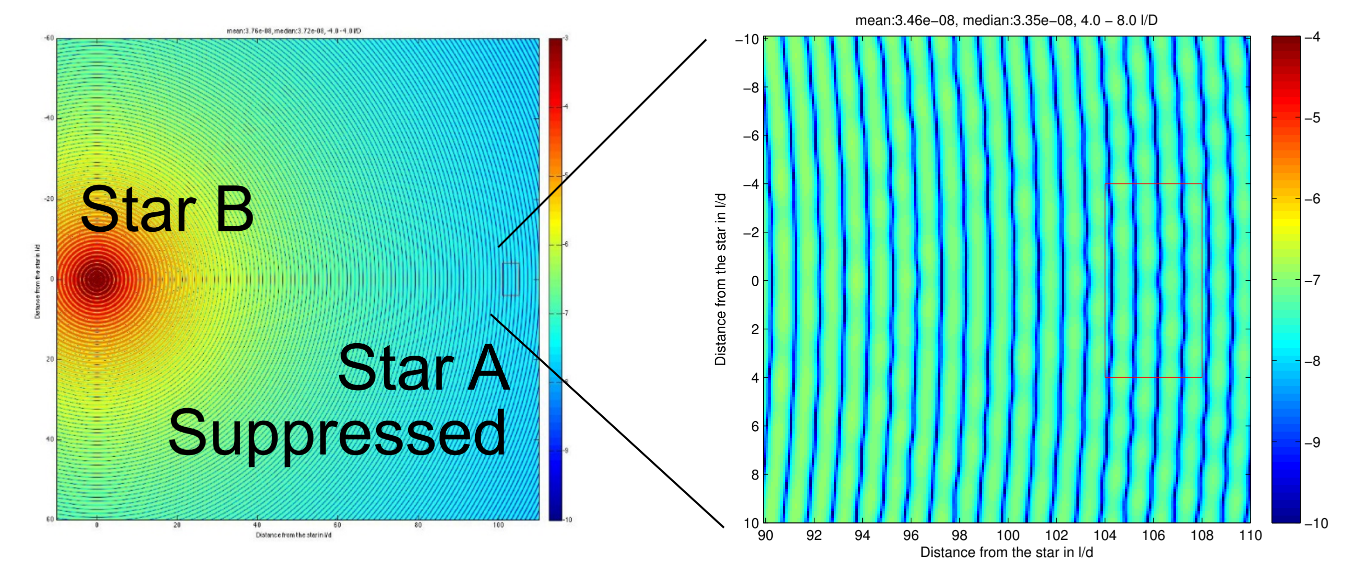
Contrast comparison

	2 star WC	On axis WC	Off axis WC
Before	1.3e-4	1e-4	7.7e-6
After	5.2e-8	4.5e-8	1.6e-9
1 star	n/a	< 1.9e-8	< 6.2e-10

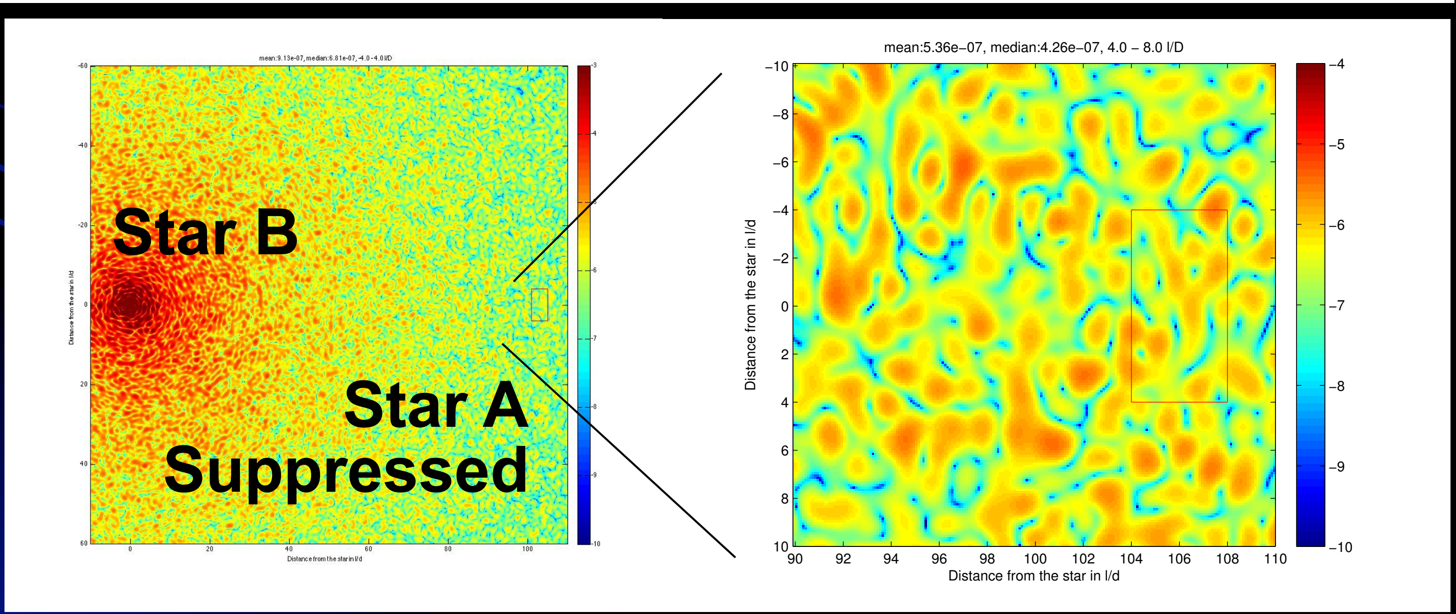




Diffraction vs. Aberrations at large angles



Diffraction from
the off axis star:
3.4 e-8 (median)



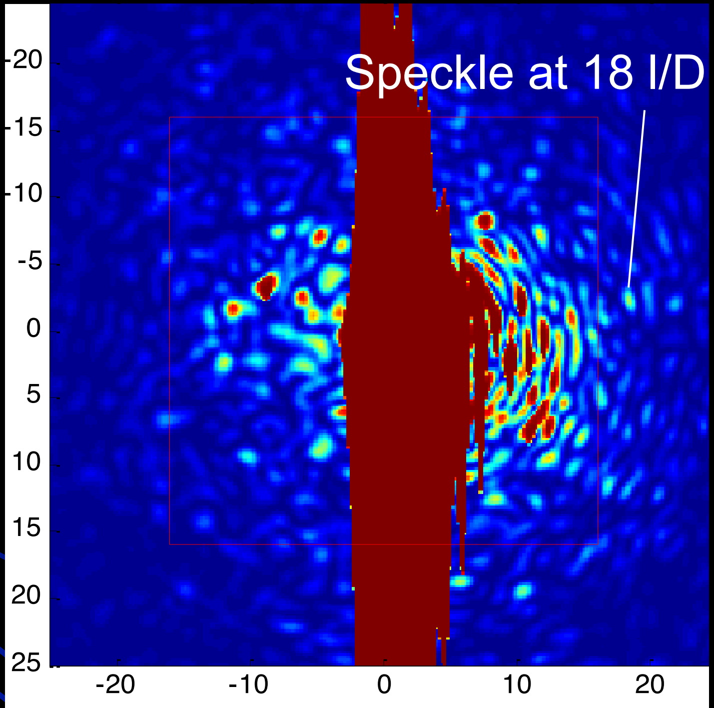
25 nm rms Aberrations

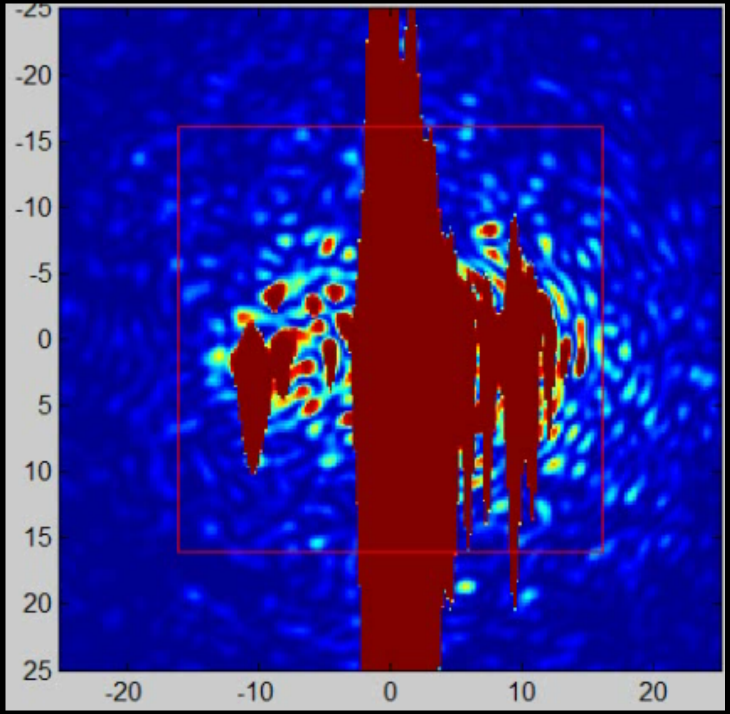
leakage from the off
axis star:
4 e-7 (median)

How to suppress the second star?

- ~~Challenge #1: Diffraction~~
- Challenge #2: Aberrations
  - Challenge #2a: Speckle suppression beyond the Nyquist frequency of DM
  - Challenge #2b: Independent speckle suppression of two (mutually incoherent) stars

Harmonic SNWC preliminary demo (for DMs without quilting)





SNWC Broadband simulations

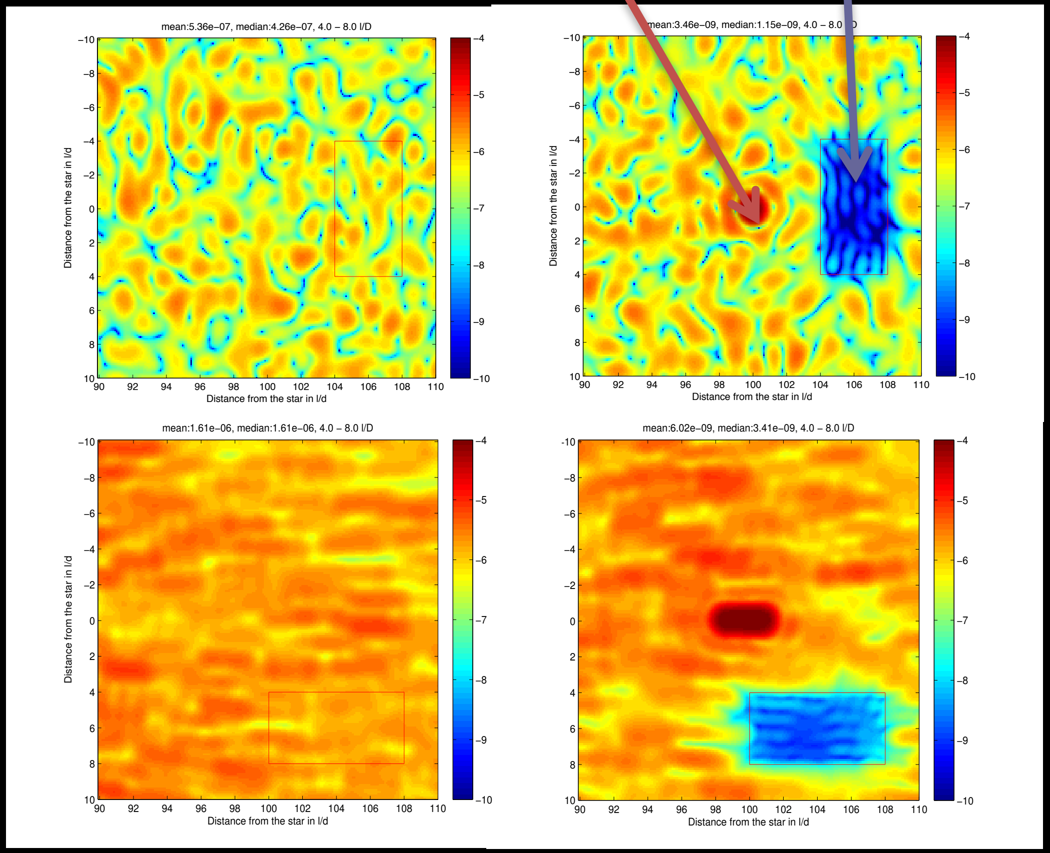
- ***Simulation example: a Cen with a 1.5m telescope***
  - Assume on-axis star is fully suppressed
  - 10” separation with a 1.5m telescope = 100 λ/D @ 770nm.
  - Diffraction grid of 50 cycles per aperture
  - Dark zone at 104 λ/d of size 4x8 λ/d region.
  - The DM used has 32x32 actuators

- ***Monochromatic 770 nm) results***
  - *Aberrations: f^{-2}, 25nm rms at 770nm*
  - Before correction: 4.26 e-7
  - After correction: **1.15 e-9**
  - Over a factor 100 improvement

- ***Preliminary broadband results***
  - ***3% wavelength band***
  - *Aberrations: f^{-2}, 20nm rms at 770nm*
  - Before correction: 1.61 e-6
  - After correction: **3.41 e-9**
  - Over a factor 100 improvement

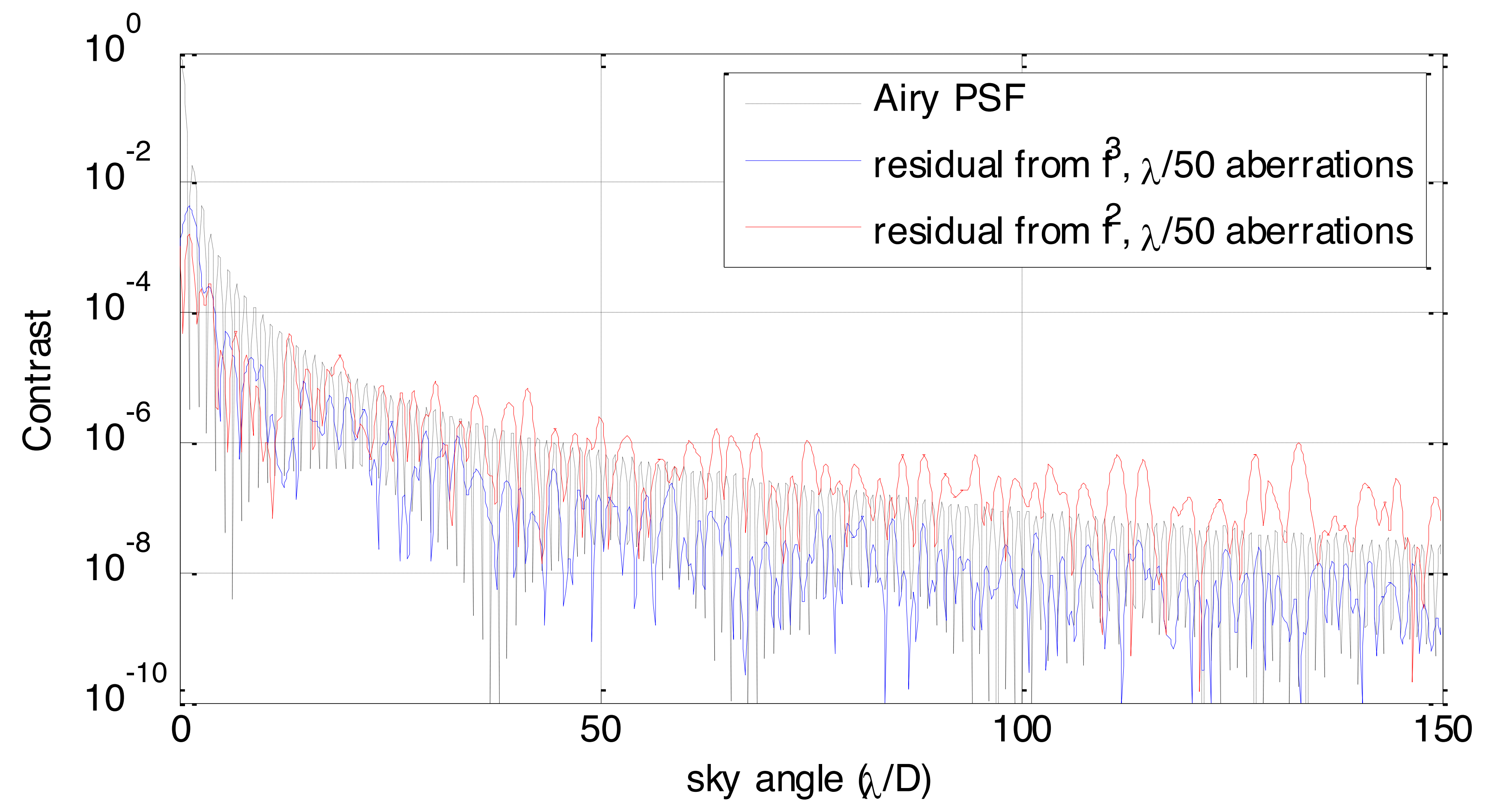
Diffracted star image at 100 λ/D

Super-Nyquist dark zone at 104 λ/D with a 32x32 DM



Thomas et al. 2015

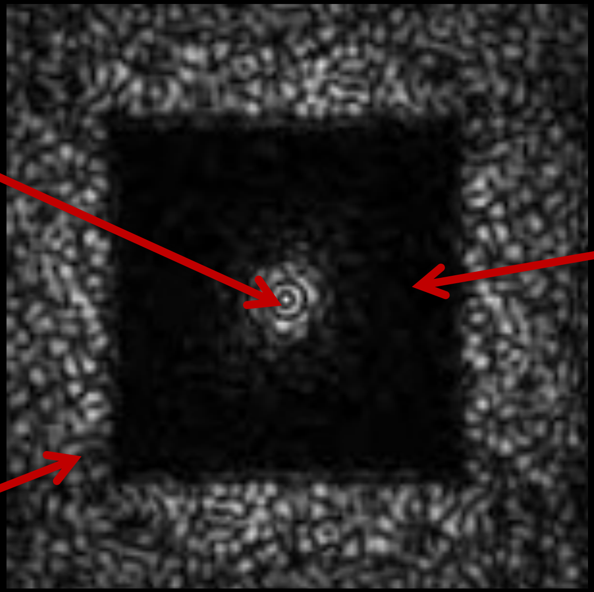
Diffraction and Aberrations



Nyquist limit of the DM: is it really a limit?

On axis light suppressed by coronagraph

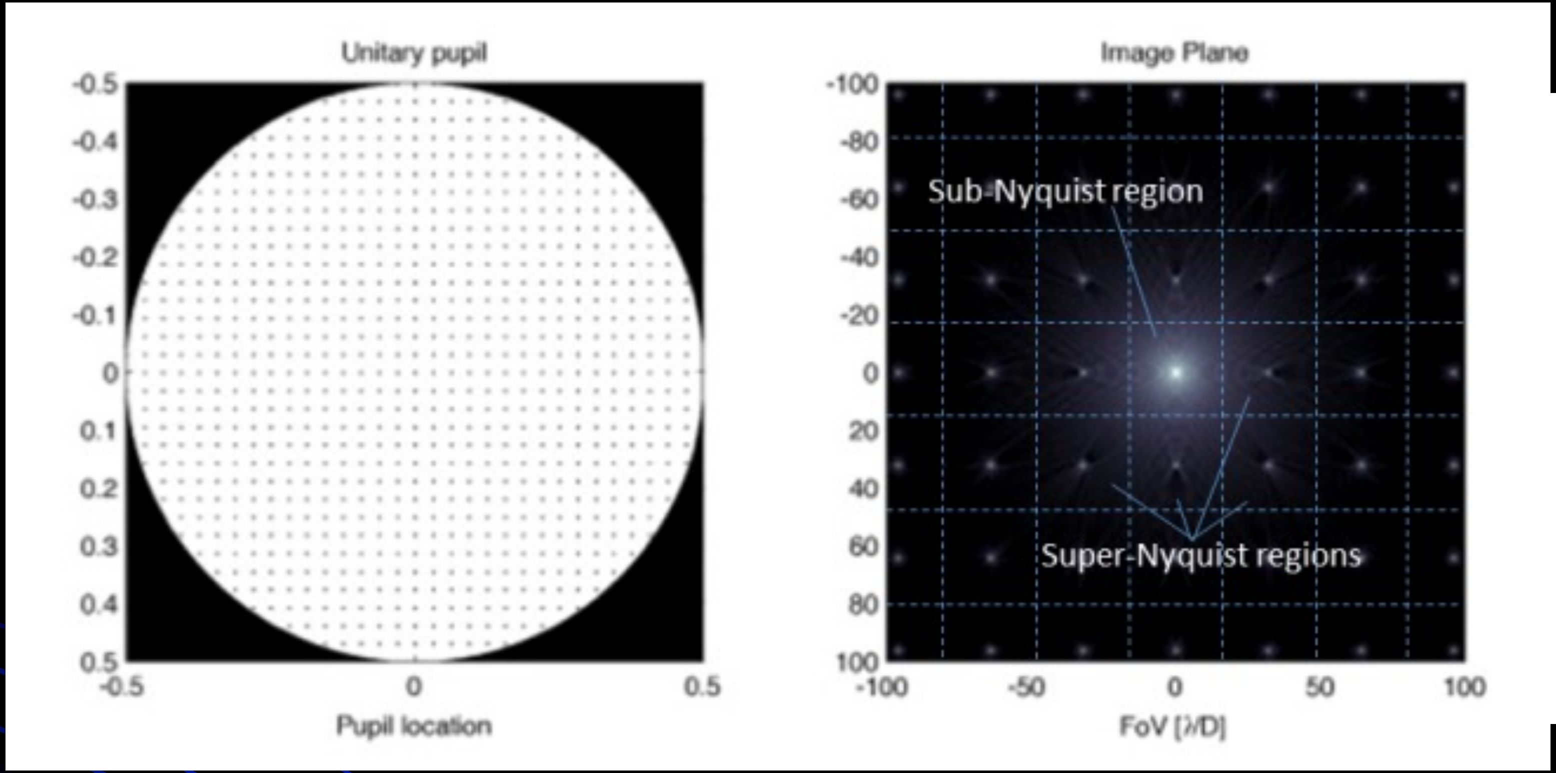
Residual speckles in the “uncorrectable” Super-Nyquist region

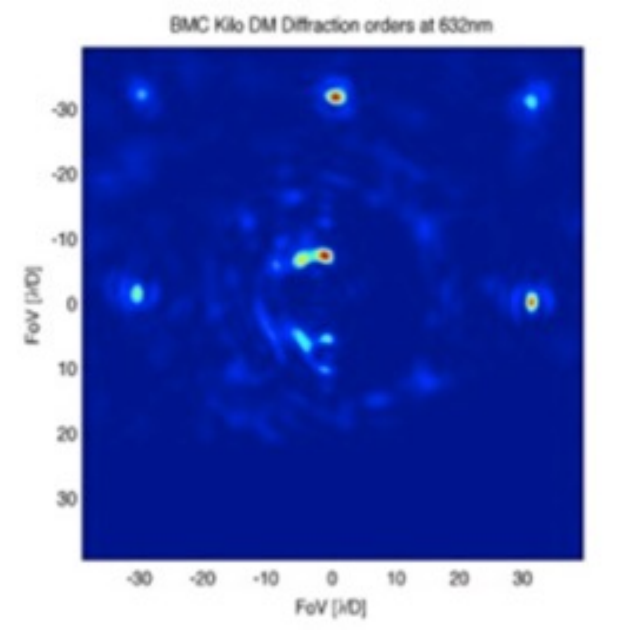


Sub-Nyquist frequency region (N/2*λ/d) = usually only of the order of a few arcsec with an 8m telescope

Credit: B. Macintosh

Super-Nyquist WC principle



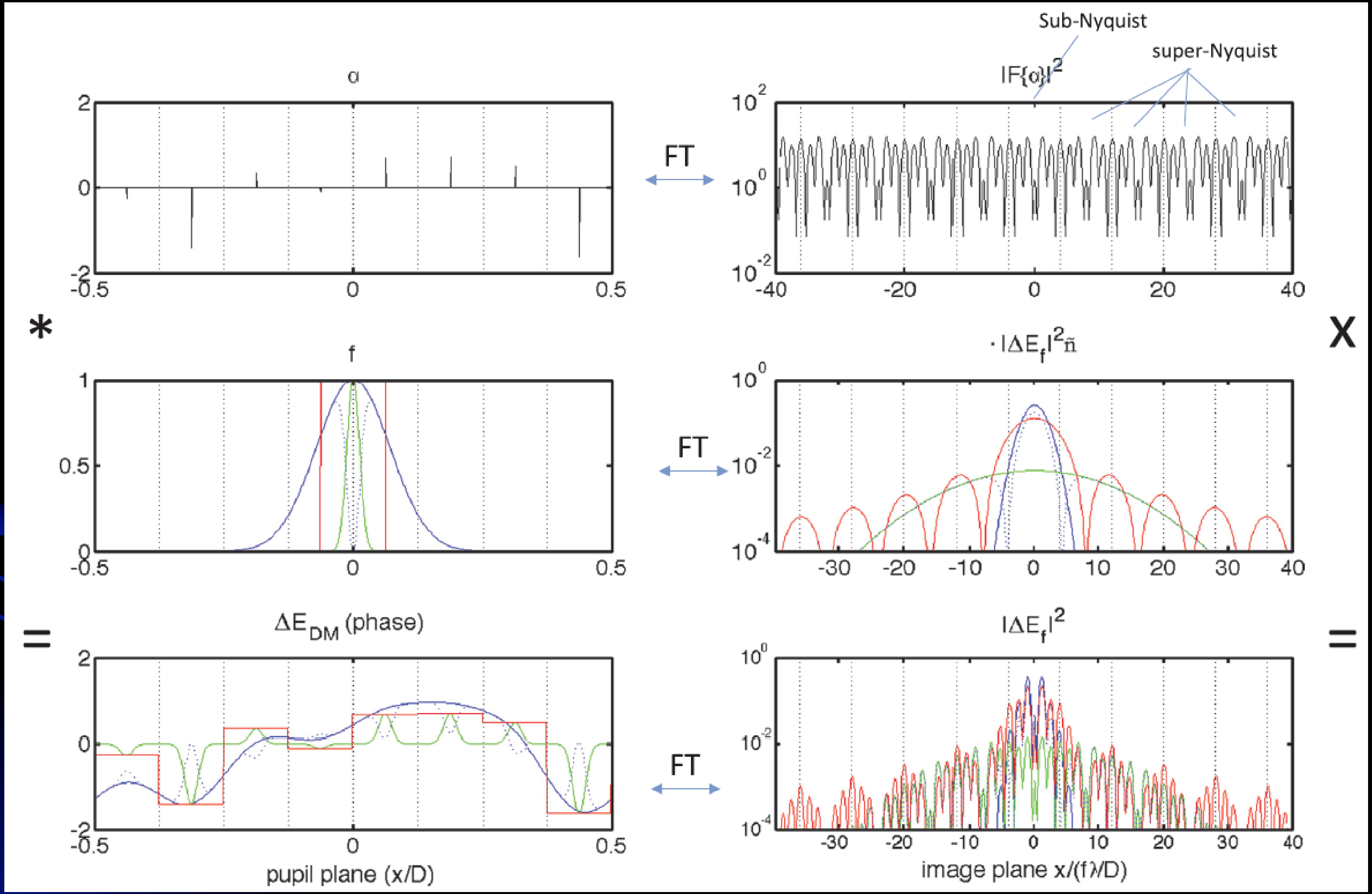


- Main idea: Diffraction orders or non-smooth influence functions enable the DM to modulate light beyond the Nyquist limit
  - Diffraction order effectively acts as a pseudo star, and almost any WF algorithm can be used to dig a dark hole (at a sub-Nyquist distance) around a diffraction order
  - Can also be understood in terms of aliasing
- If grating periodicity = DM actuator periodicity, then controllable diffraction order regions fully tile the entire focal plane (theoretically to infinity)

SNWC using influence functions

Pupil plane

Focal plane



DM actuator coefficients

Influence functions

DM field perturbation

SNWC Controllability ←

SNWC using quilting or grating

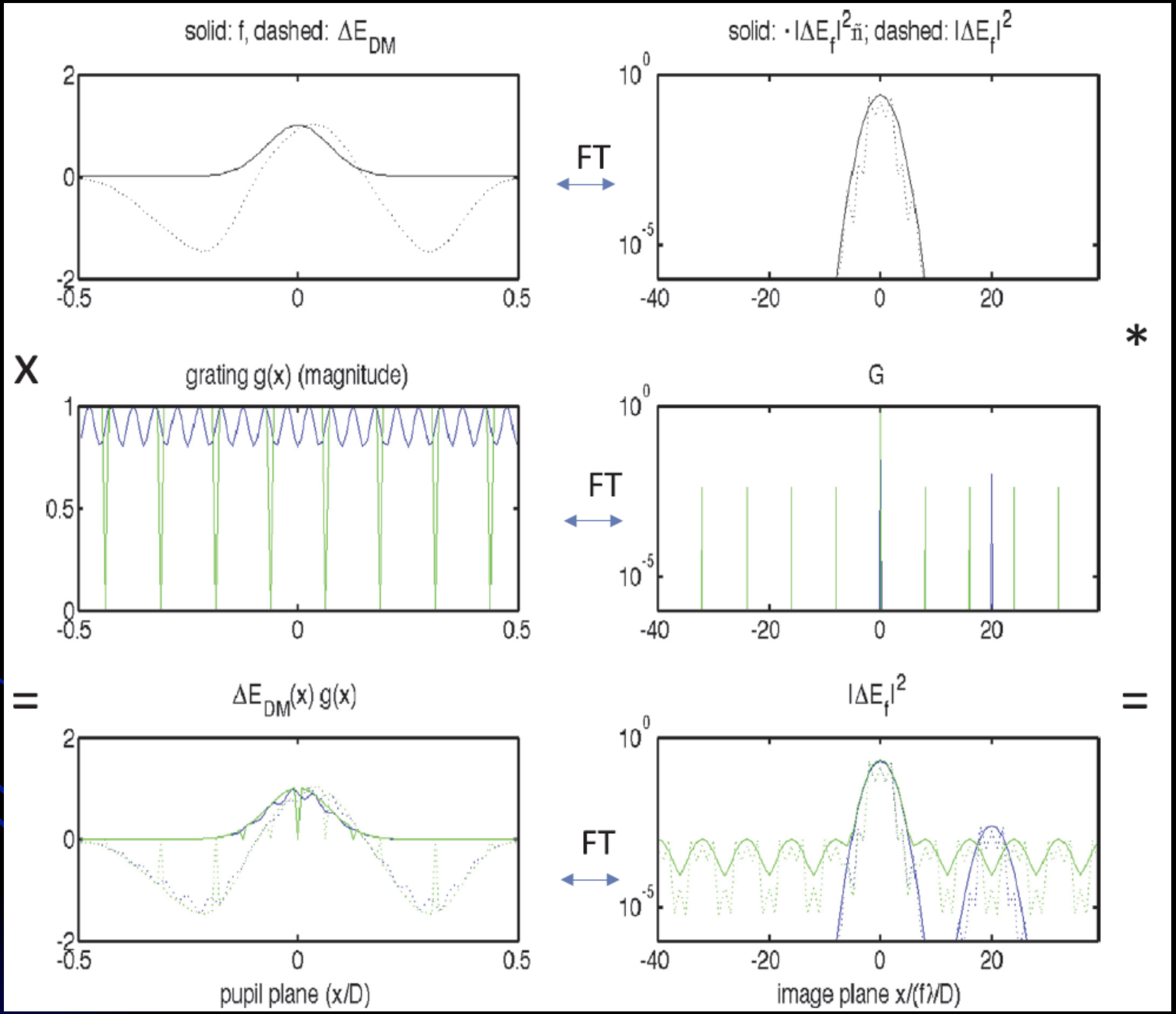
Pupil plane

Focal plane

Solid: influence function
Dashed: DM field perturbation

Grating (green) or beamsplitter (blue)

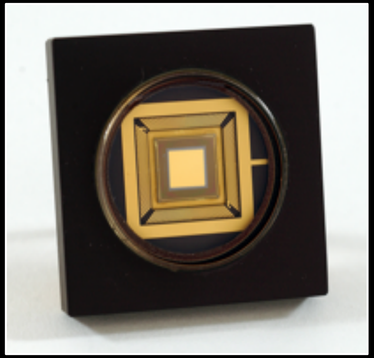
DM field perturbation

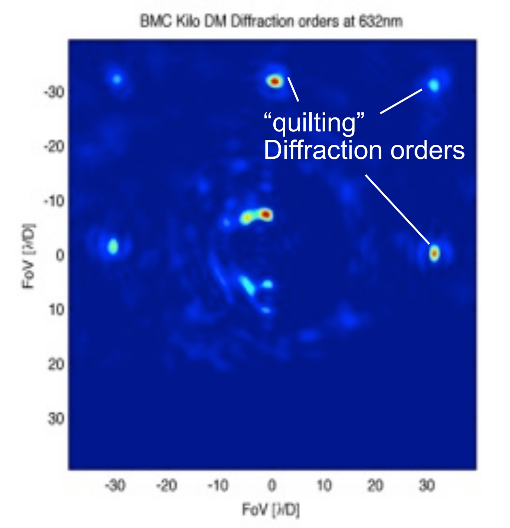


Sub-Nyquist controllability curve

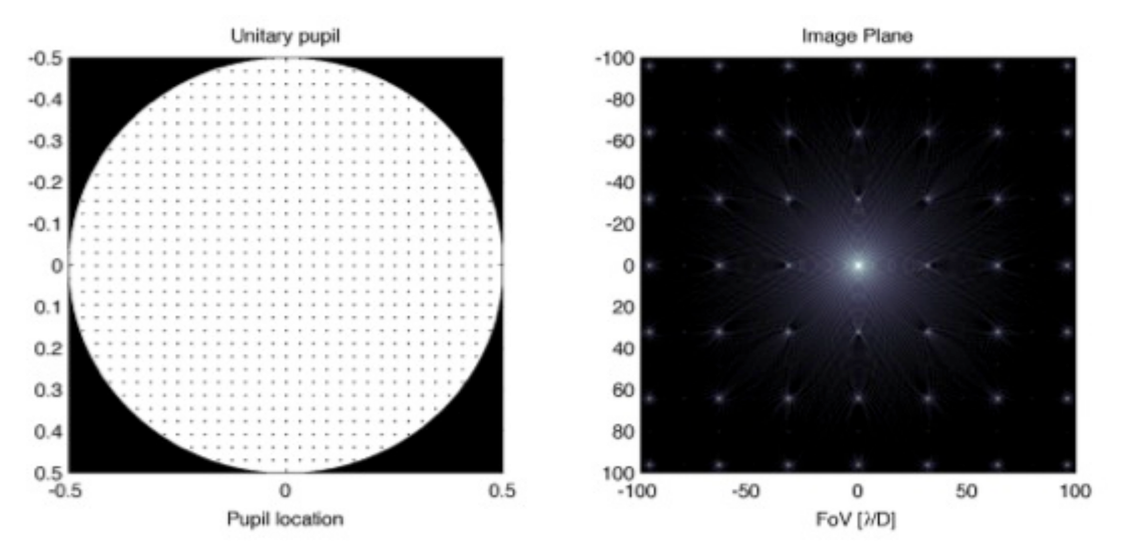
Super-Nyquist controllability curves (solid)

Challenge 2a solution:
Super-Nyquist Wavefront Control



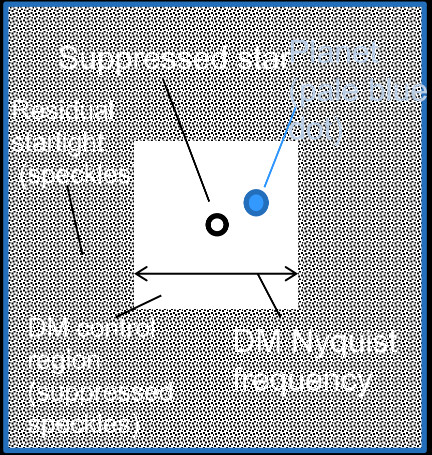


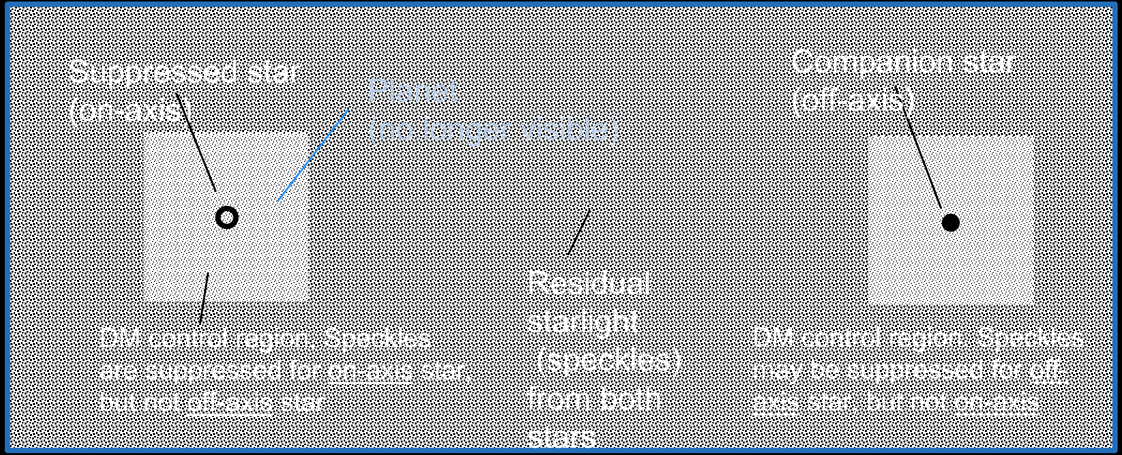
“quilting” Diffraction orders



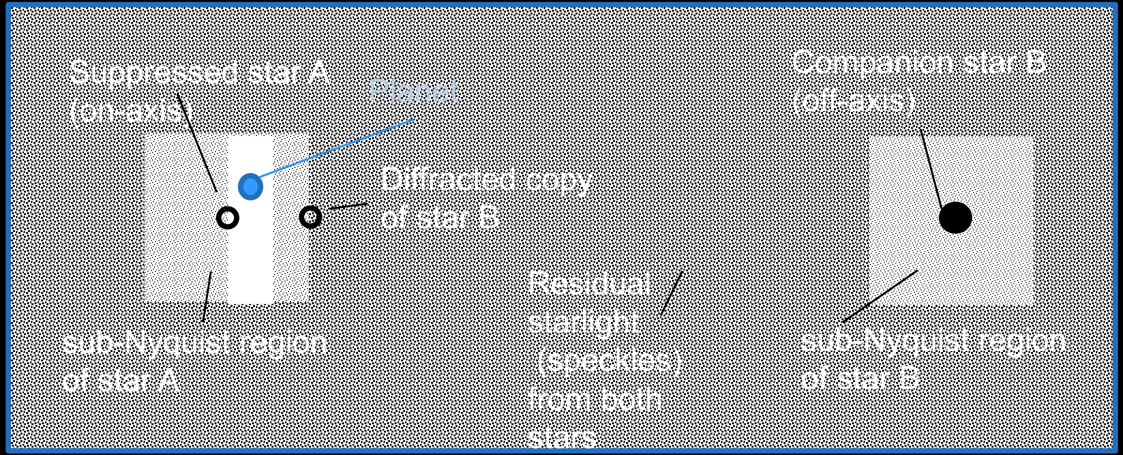
- Two approaches:
- Aliasing from diffraction orders
  - Using DM quilting or segmented DMOr a diffractive pupil
- 2nd order diffraction from nonlinearity between DM shape and Electric Field

Putting it all together

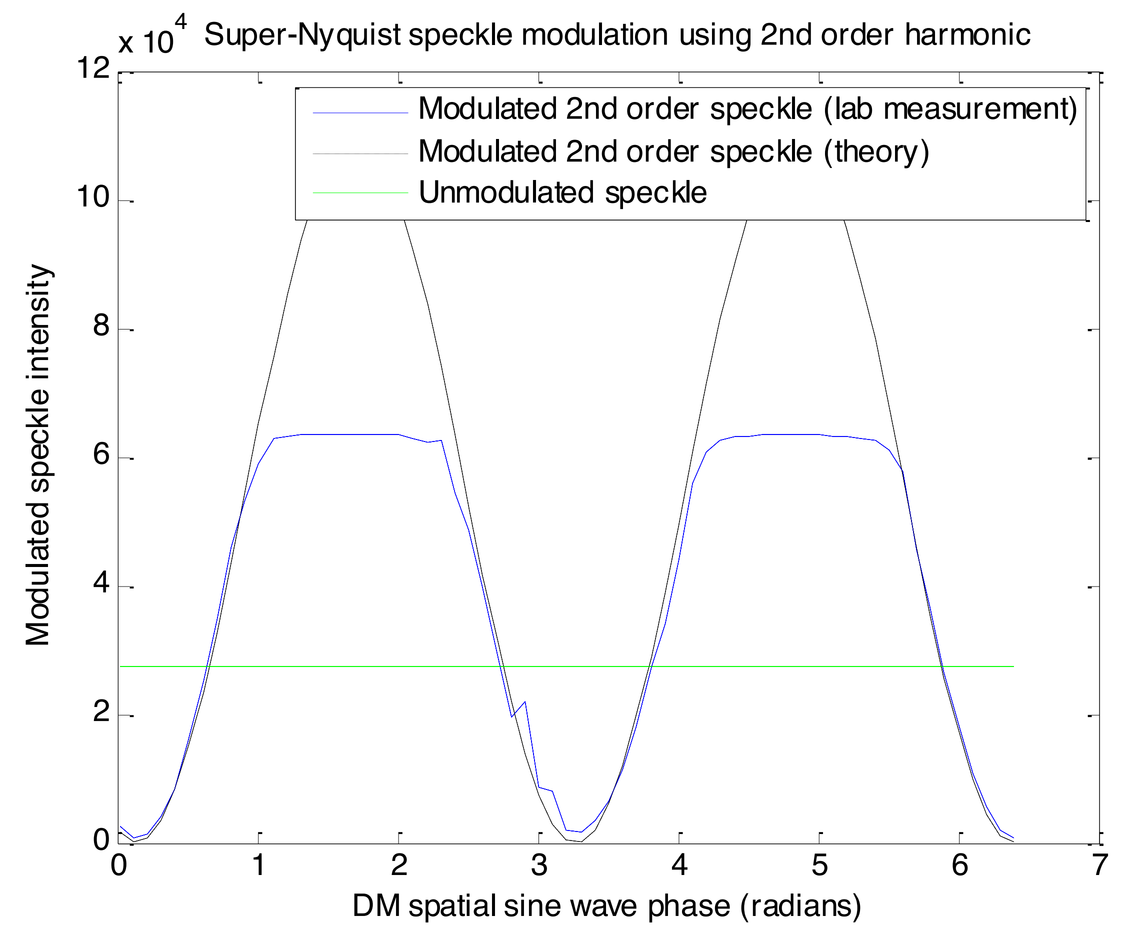

Suppressed star
Planet (pale blue dot)
Residual starlight (speckles)
DM control region (suppressed speckles)
DM Nyquist frequency


Suppressed star (on-axis)
Planet (no longer visible)
Companion star (off-axis)
Residual starlight (speckles) from both stars
DM control region. Speckles are suppressed for on-axis star, but not off-axis star
DM control region. Speckles may be suppressed for off-axis star, but not on-axis

- Challenge 1: outside DM control region
  - Super-Nyquist WC
- Challenge 2: speckles from both stars are incoherent
  - Multi-star WC
- Combination:
  - MSSNWC


Suppressed star A (on-axis)
Planet
Companion star B (off-axis)
Diffracted copy of star B
Residual starlight (speckles) from both stars
sub-Nyquist region of star A
sub-Nyquist region of star B

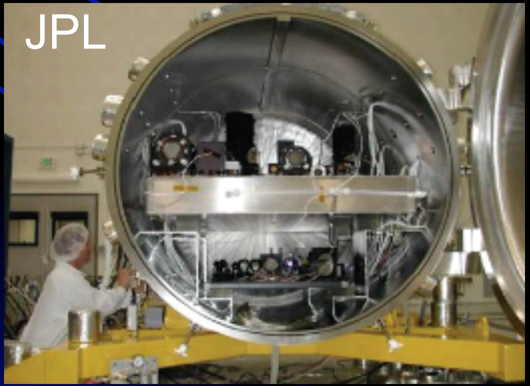
Model validation of harmonic speckle modulation

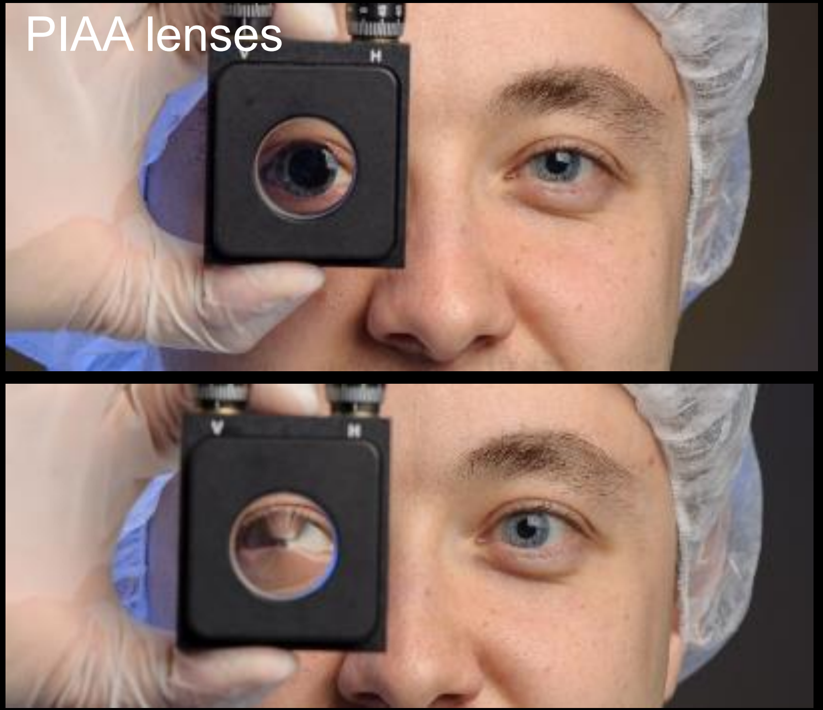


Testbeds and PIAA hardware

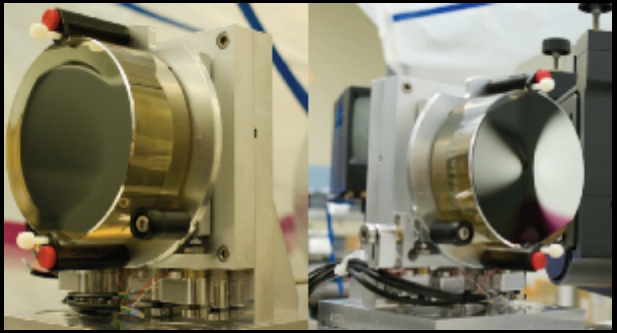

ACE testbed


Lockheed Martin

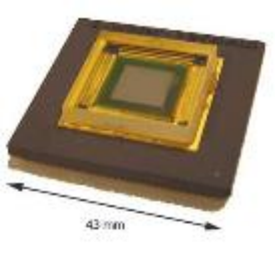

JPL


PIAA lenses

PIAA mirrors



Deformable mirror



State of the art performance in the lab

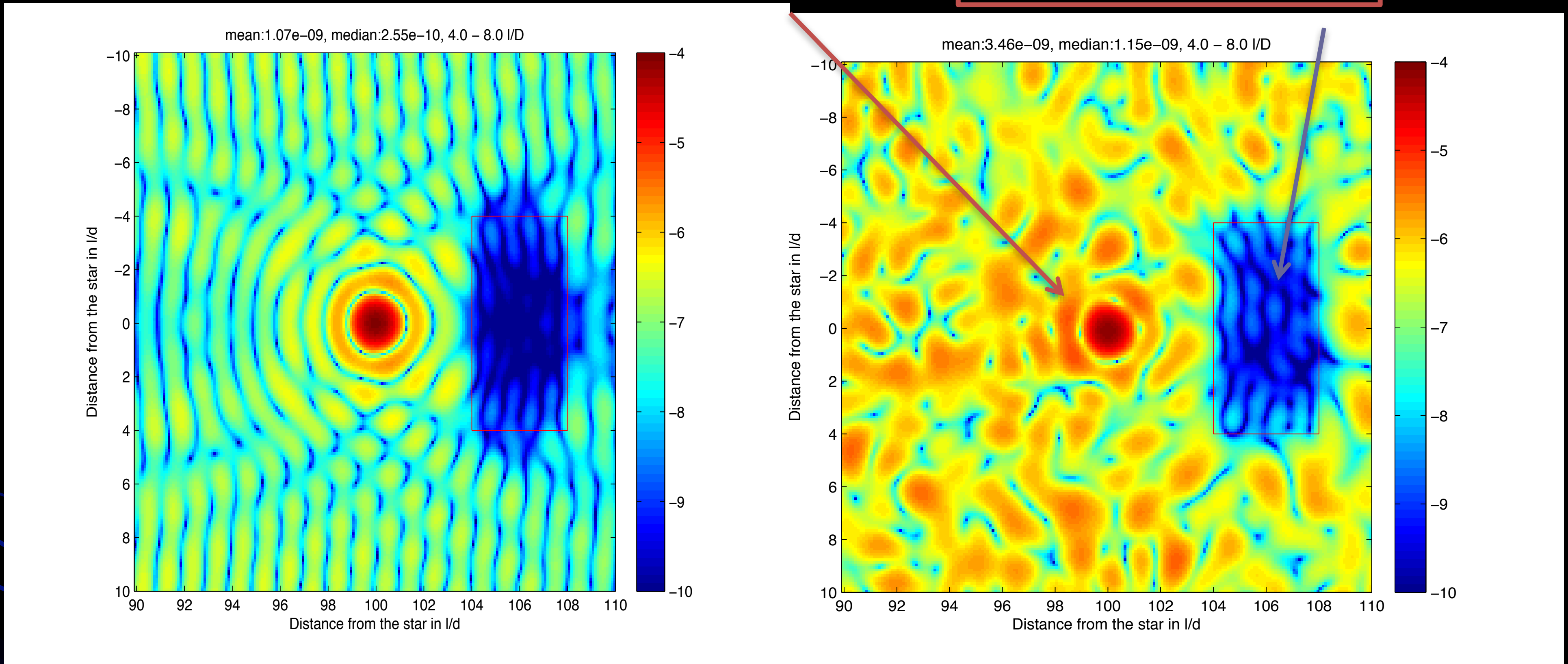
Ruslan Belikov, NASA Ames Coronagraph Laboratory

Super-Nyquist Wavefront Control

With a grid of 50 cycles per aperture, 100 lambda/d, 4x8 lambda/d region, monochromatic, 770 nm

Diffracted star image at 100 λ/D

Super-Nyquist dark zone at 104 λ/D with a 32x32 DM



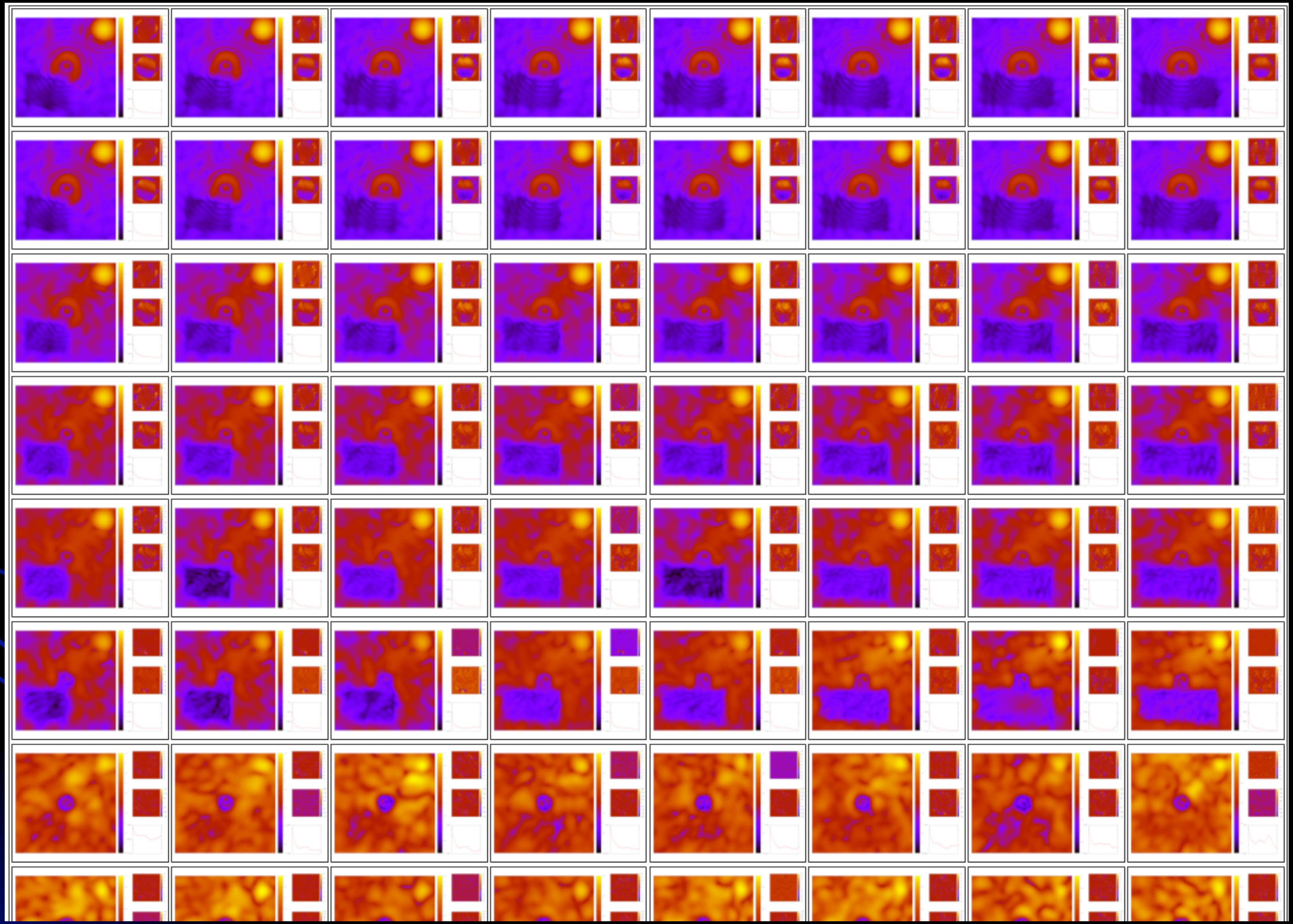
No aberrations

25nm rms

Before correction: 3.35 e-8
After correction: 2.55 e-10
Factor 100 improvement

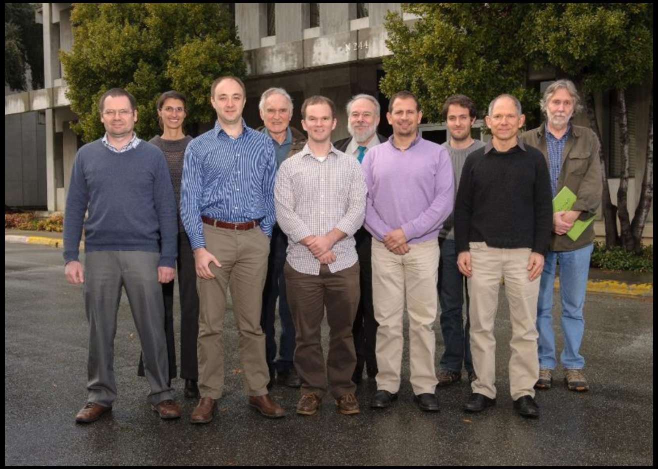
Before correction: 4.26 e-7
After correction: 1.15 e-9
Over a factor 100 improvement

Supercomputer optimizations



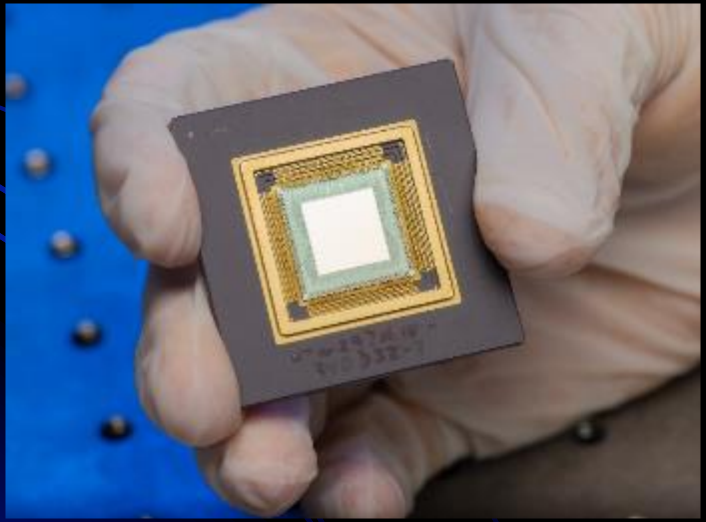
Ames Coronagraph Experiment (ACE) Laboratory

Team

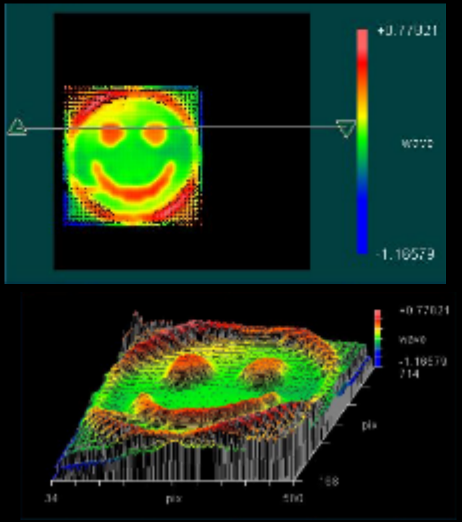


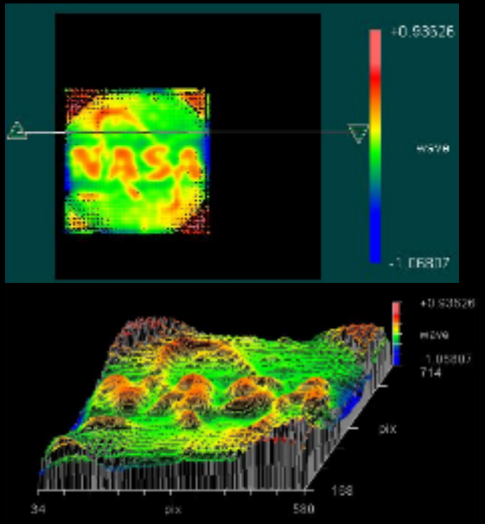
Thermally stabilized testbed

BMC DM: 32 x 32 actuators



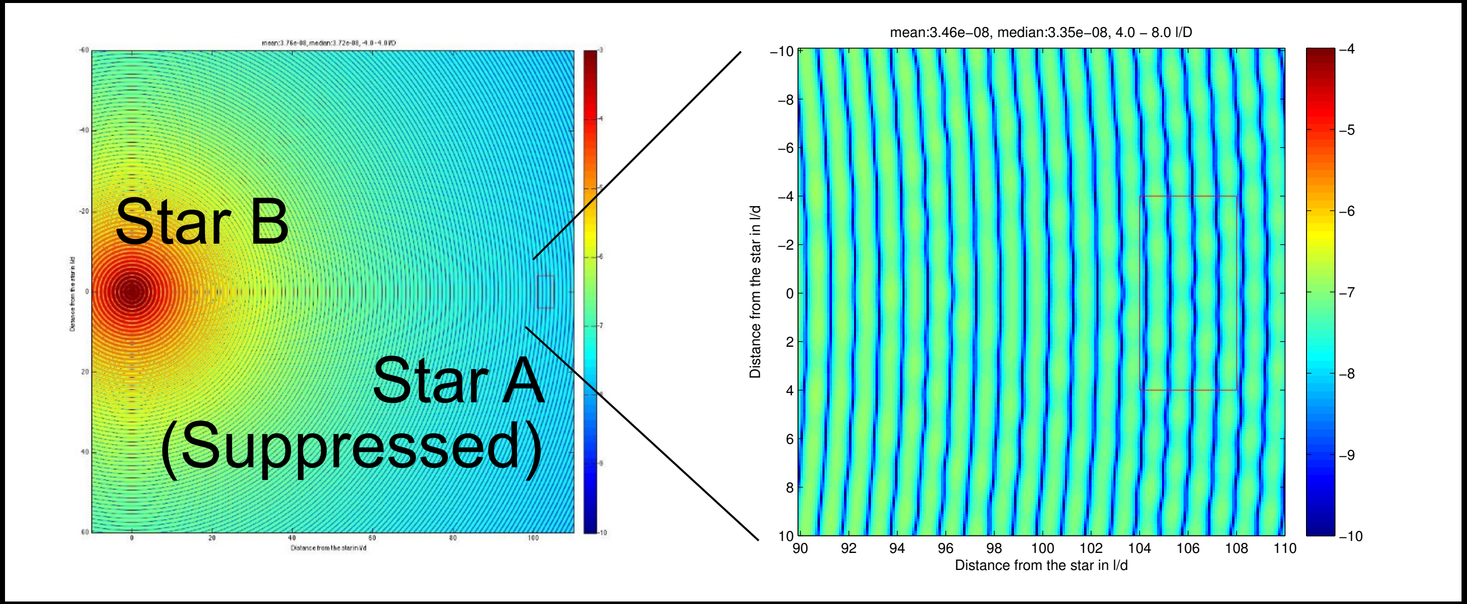
(see Bendek et al. 9909-299 for a new compact DM driver)



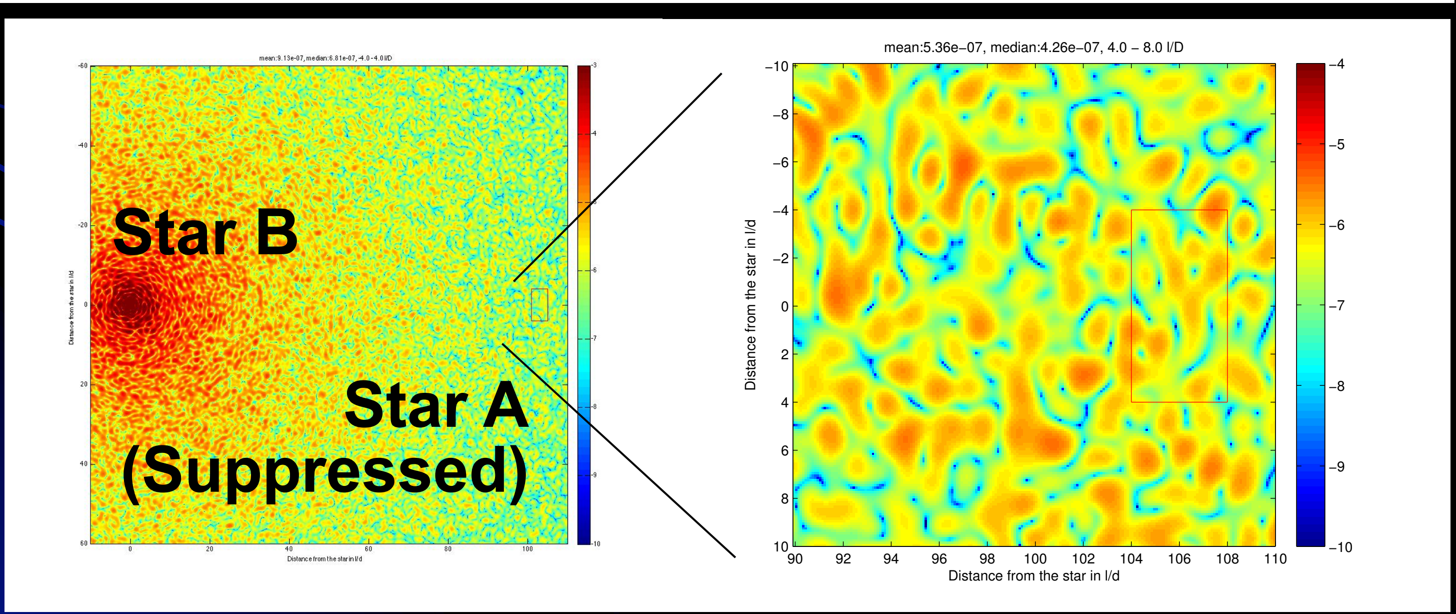


Ruslan Belikov, NASA Ames Coronagraph Laboratory

What if star separation is beyond DM control region?



Diffraction from
the off axis star:
3.4 e-8 (median)

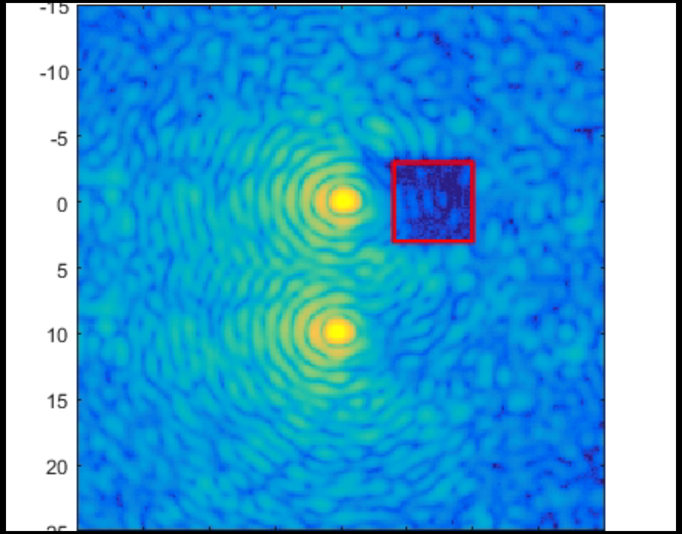


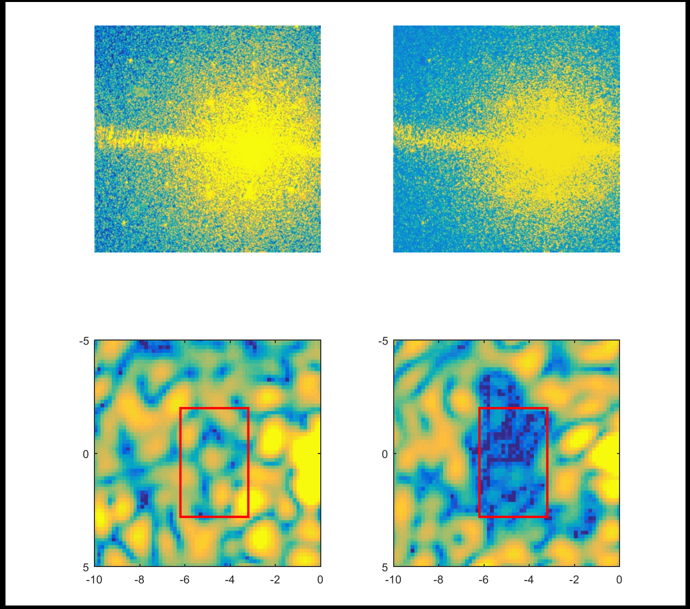
25 nm rms Aberrations

leakage from the off
axis star:
4 e-7 (median)

Conclusions

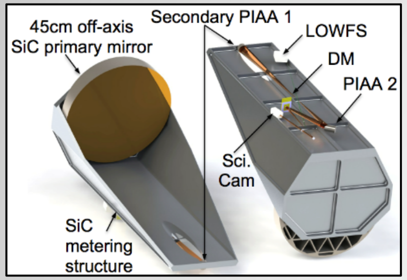
- Multi-star high contrast imaging opens up the majority of (non-M-dwarf) star systems
  - Alpha Centauri in particular
- Main challenge seems to be in wavefront control algorithms
  - Existing mission designs may already be capable of some multi-star high contrast imaging
- Milestones met on budget and on schedule
  - Lab demo of MSWC
  - Lab demo of SNWC

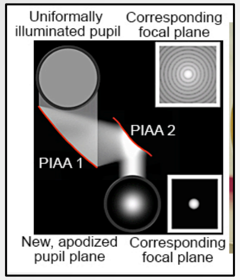


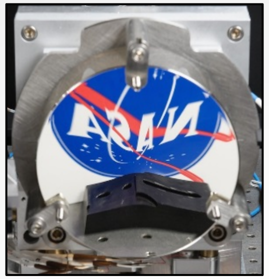


Instrument Building blocks

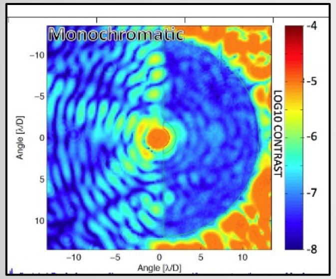
45 cm off-axis telescope with an **embedded** PIAA -> 10^{-5} (1.6 – 10λ/D)

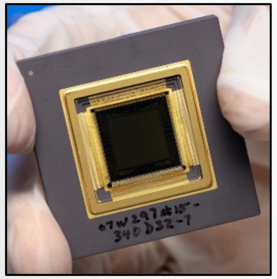


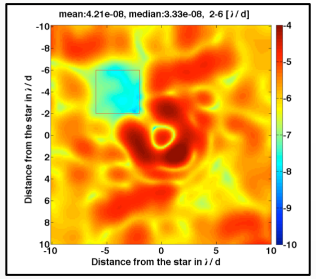




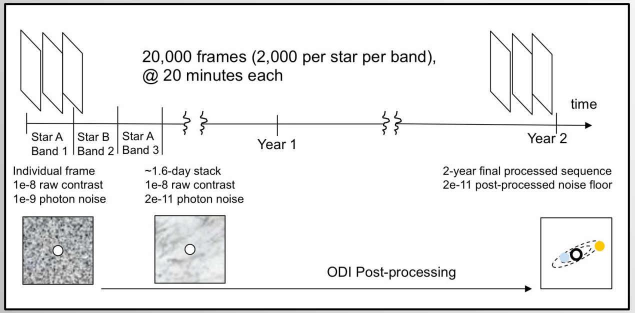
WFC (Multi-Star Wave Front Control) -> 10^{-8}

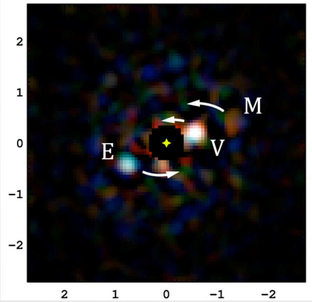


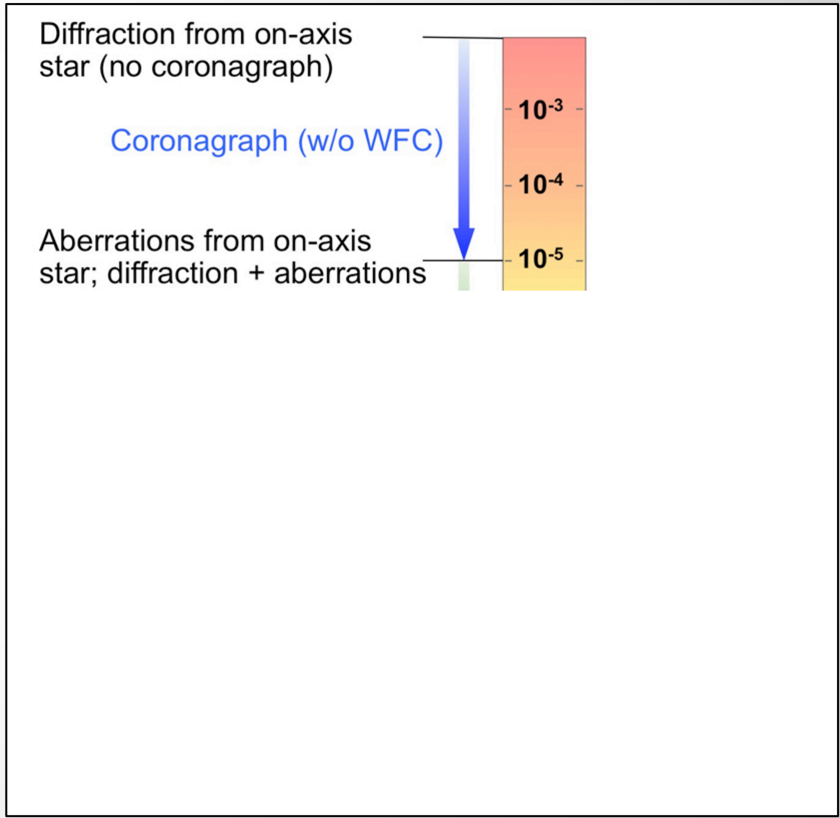




Continuous observation ODI -> 10^{-11}





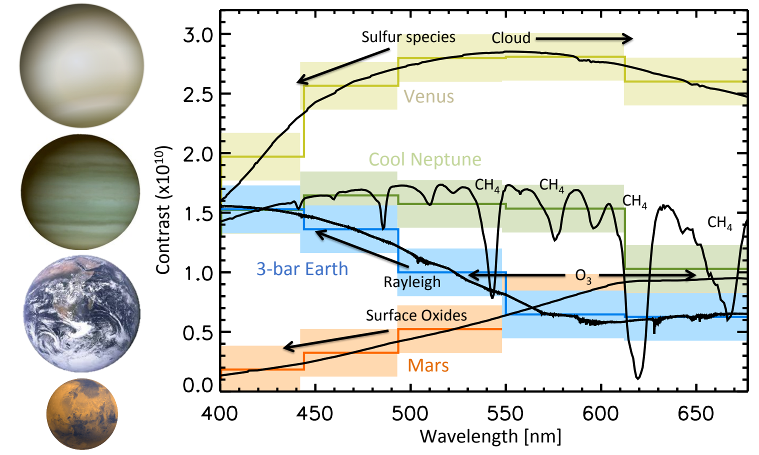


Diffraction from on-axis star (no coronagraph)

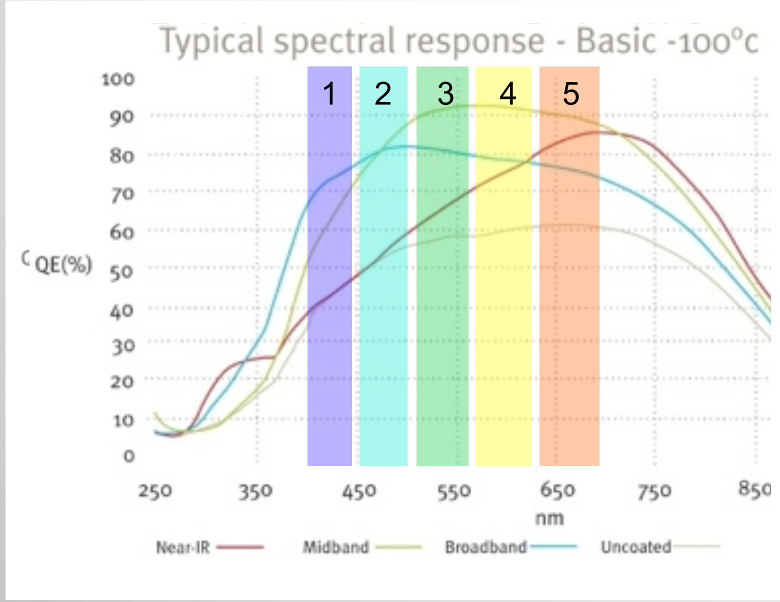
Coronagraph (w/o WFC)

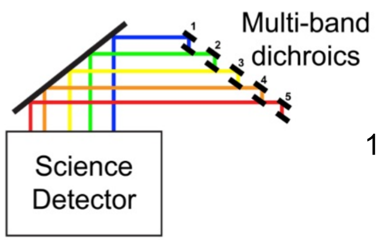
Aberrations from on-axis star; diffraction + aberrations

Multi-Spectral Imager

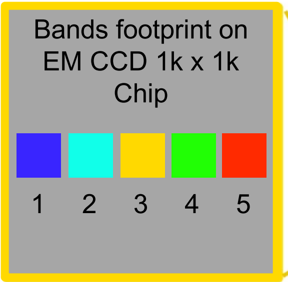


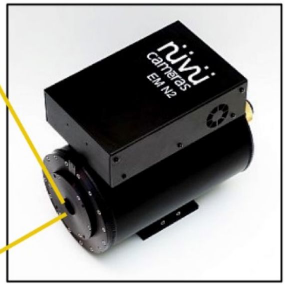
- Wavelength: **400 nm to 700 nm** (Contains 40% aCen A flux)
- **Five channels** of 10% bandwidth each.
- **SW (400nm):** Blue rayleigh scattering indicates **earth-like atmosphere**. (Const. coatings and QE)
- **LW (700): CH_4 absorption bands**. Limited by QE and WFC bandwidth.





4" HFoV
100 x 100px
0.31" resolution
13.3µm pitch [px]
5 bands @10%



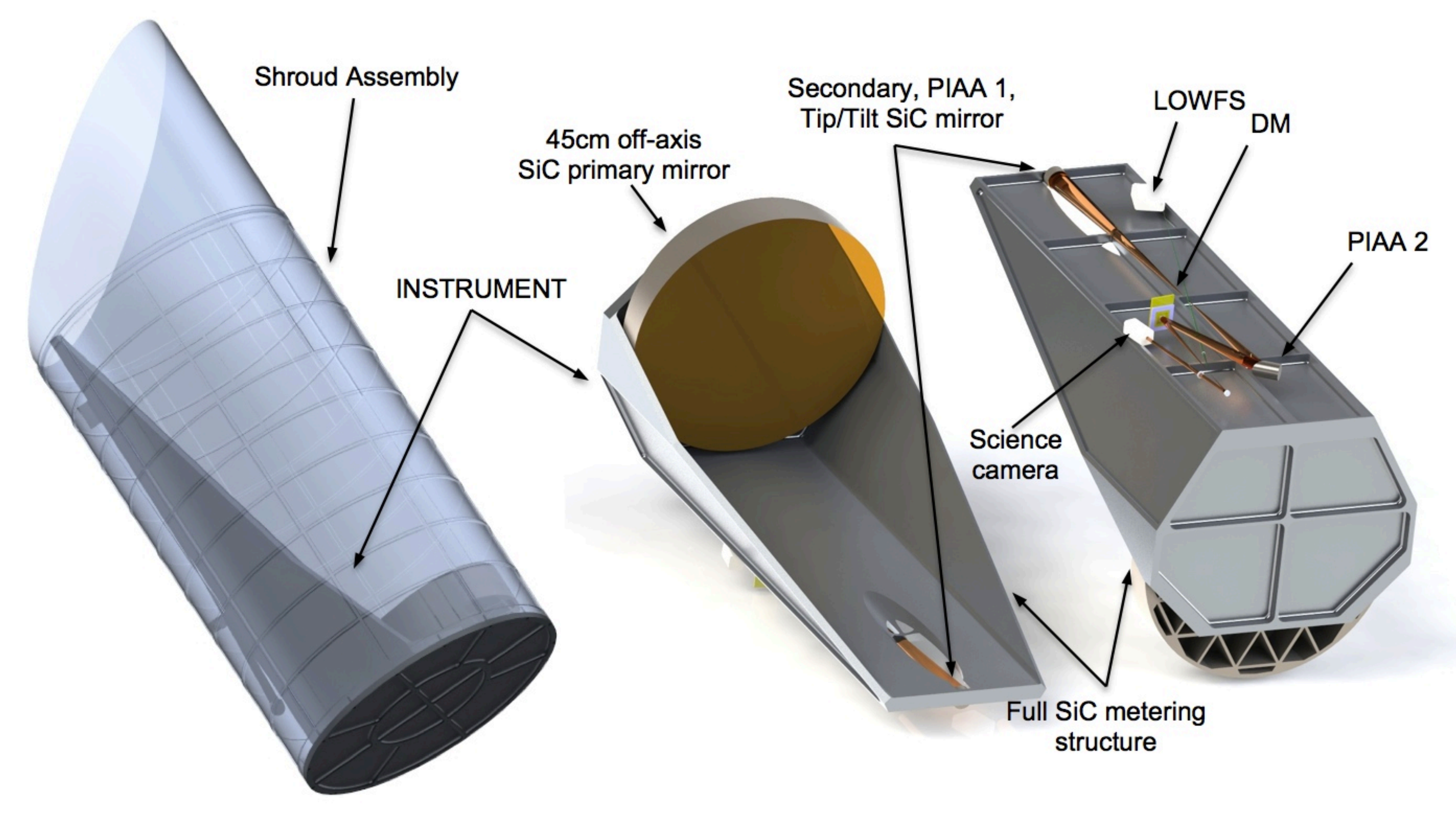


Nuvu Camera

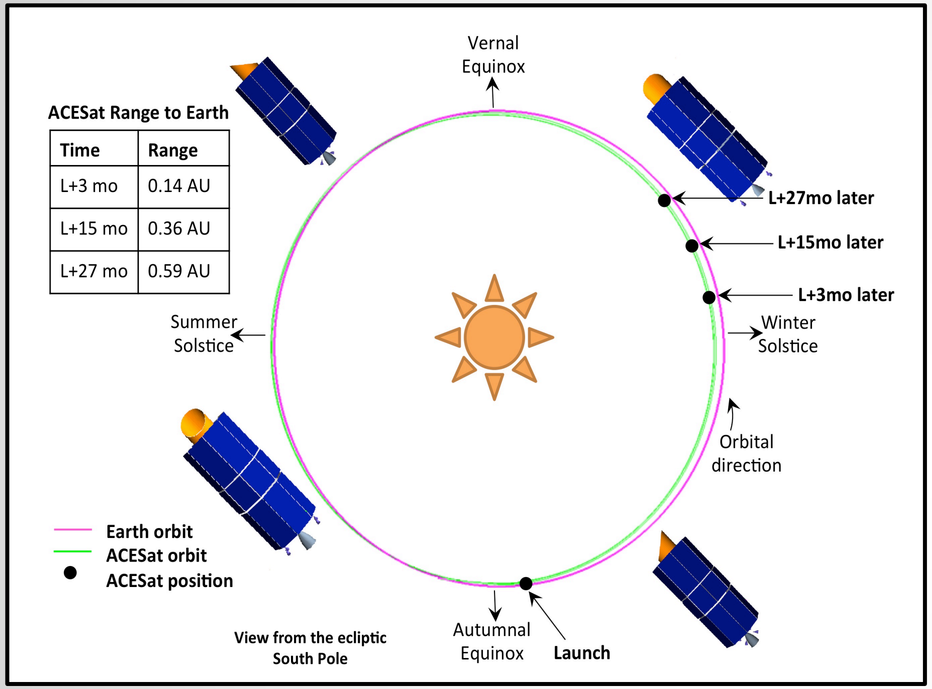
- E2v EMCCD 201-20 **almost zero RON**
- Short 10s exposure time to avoid cosmic rays

Telescope Hardware

- Full SiC 45cm, Off-axis telescope, L/25 max end-to-end WFE (Total 45Kg mass)
- Active thermal control to maintain 10˚C operation with 0.1˚C PV stability
- 0.5mas RMS stability LOWFS (Demonstrated for CAT III EXCEDE Lockheed Martin)



Mission operations



ACESat Range to Earth

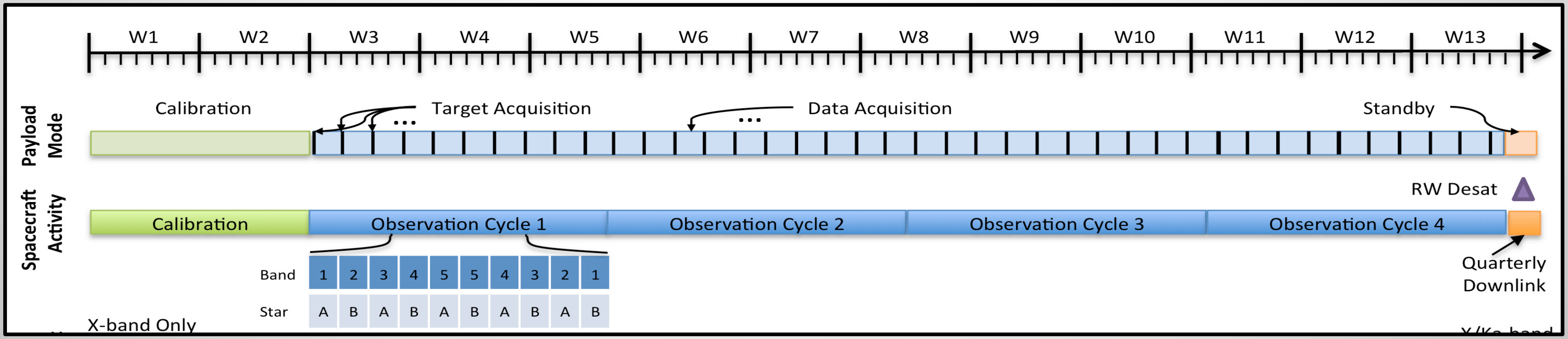
Time	Range
L+3 mo	0.14 AU
L+15 mo	0.36 AU
L+27 mo	0.59 AU

High stability pointing spacecraft

Unperturbed observation per quarter, 1.6 days/band/star

Quarterly operations:

- **DSN Downlink** and reaction wheels desaturation and quarter end.
- **90˚ Roll** to keep sunshield in position
- **Calibration** per quarter (Speckle MSWC, LOWFS).



Band	1	2	3	4	5	5	4	3	2	1
Star	A	B	A	B	A	B	A	B	A	B

SNWC Main design constraints

- Location: a diffraction order is required within a sub-Nyquist distance of desired dark hole
  - This is guaranteed if grating periodicity = DM pitch
- Energy conservation: total speckle energy to be suppressed < total energy of active diffraction order. For example, 32x32 DM and a 1e-3 diffraction order:
  - Up to 10^{-4} speckles in a 3 x 3 l/D region
  - Up to 10^{-6} speckles in a 32 x 16 l/D region
- Conservation of degrees of freedom: SNWC allows shifting the sub-Nyquist dark zone beyond the Nyquist limit, but does not allow enlarging it
  - Multiple dark zones can be stitched to achieve a larger dark zone
- Blind spots at locations of the diffraction orders
  - Telescope can be rotated to move them away